Search for the Decay $B^0 \to \gamma\gamma$

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We present a limit on the branching fraction for the decay $B^0 \to \gamma\gamma$ using data collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- collider. Based on the observation of one event in the signal region, out of a sample of 21.3×10^6 $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ decays, we establish an upper limit on the branching fraction of $\mathcal{B}(B^0 \to \gamma\gamma) < 1.7 \times 10^{-6}$ at the 90% confidence level. This result substantially improves upon existing limits.

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In the standard model the decay $B^0 \to \gamma\gamma$ proceeds via a second order weak transition, including gluonic penguins, followed by annihilation (Fig. 1). Standard model predictions for the branching fraction of these effective

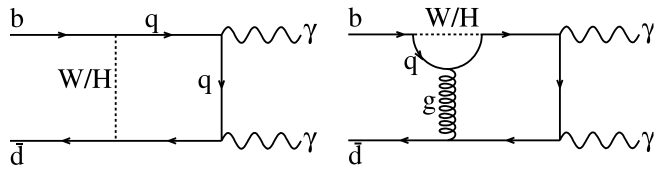

FIG. 1. Examples of possible diagrams responsible for the decay $B^0 \to \gamma\gamma$. In these diagrams $q = u$, c, or t, and H is a hypothetical charged non-standard-model Higgs boson.

flavor-changing weak neutral current processes range from 0.1 to 2.3×10^{-8} [1].

Physics beyond the standard model can enhance this branching fraction by as much as 2 orders of magnitude, particularly in the case of two-Higgs models [2]. Other particles from the supersymmetric spectrum can further modify the standard model expectation [1]. The current best limit on the branching fraction for $B^0 \to \gamma\gamma$, from the L3 experiment [3] at the CERN LEP collider, is $\mathcal{B}(B^0 \to \gamma\gamma) < 3.9 \times 10^{-5}$ (90% confidence level).

In this Letter we present an analysis based on data taken with the *BABAR* detector [4], which operates at the PEP-II asymmetric-energy e^+e^- collider at the Stanford Linear Accelerator Center [5]. The sample consists of 19.4 fb^{-1} taken at the $\Upsilon(4S)$ resonance, corresponding to 21.3×10^6 $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ events. An additional sample of 2.2 fb^{-1} accumulated 40 MeV below the $\Upsilon(4S)$ resonance is used to estimate non-$B\overline{B}$ background.

Charge conjugation invariance is assumed for all channels quoted in this paper, and the charge conjugate reactions are included in the analysis. Quantities evaluated in the $\Upsilon(4S)$ rest frame are denoted by an asterisk, e.g., E_b^* is the energy of the e^+ and e^- beams in the $\Upsilon(4S)$ rest frame.

The *BABAR* detector, a general purpose solenoidal magnetic spectrometer, is described in detail elsewhere [4]. A silicon vertex detector and a cylindrical drift chamber in a 1.5-T solenoidal magnetic field are used to measure momenta and ionization energy loss of charged particles. Electrons and photons are identified by a CsI electromagnetic calorimeter (EMC).

This analysis exploits in particular the information provided by the EMC consisting of 6580 CsI crystals, covering 90% of 4π in the $\Upsilon(4S)$ rest frame. The energy resolution has been measured directly with a radioactive source at low energy and with electrons from Bhabha scattering at high energy. The mass resolution of π^0 and η candidates in which the two photons in the decay have approximately equal energy can be used to infer the energy resolution at an energy less than 1 GeV; the decay $\chi_{c1} \to J/\psi\gamma$ provides an additional measurement at 500 MeV. A fit to the energy dependence results in $\sigma_E/E = (2.3 \pm 0.3)\%/\sqrt[4]{E/\mathrm{GeV}} \oplus (1.9 \pm 0.1)\%$ [4].

Energy deposits in the EMC are reconstructed by grouping adjacent crystals with energy deposits greater than 1 MeV into *clusters*. Clusters with more than one local energy maximum are then split into *bumps*. The energy of each crystal is divided among the bumps by an iterative adjustment of the centers and energies of the bumps assuming electromagnetic shower shapes [4]. Next, all tracks reconstructed in the tracking volume are extrapolated to the EMC entrance and a track-bump matching probability is calculated for each pair.

All bumps with a matching probability smaller than 10^{-6} are treated as photon candidates. Photons are selected by requiring the bump shape to be compatible with an electromagnetic shower, and by requiring the bump to have a minimum energy of 30 MeV. In addition we accept only photon candidates which are isolated from any other bump in the event. This requirement selects against background from high-energy π^0 mesons, where the two photons from the decay of the π^0 meson strike the calorimeter in close proximity (*merged* π^0).

The *BABAR* detector is simulated by a GEANT-based Monte Carlo procedure [6] that includes beam-related background by mixing random trigger events into the Monte Carlo generated events. The simulated events are processed in the same manner as the data. The simulation is used to study background and optimize selection criteria, but only enters the analysis directly through the calculation of the signal efficiency.

In order to select $B\overline{B}$ events, we require at least three tracks of good quality in the event. The quality requirements for these tracks include a small impact parameter with respect to the collision point along the beam direction (10 cm) and transverse to it (1.5 cm), a minimum number of 13 hits in the drift chamber, and a momentum of $p < 10$ GeV/c in the laboratory frame. To help reject continuum background, the ratio of the second Fox-Wolfram moment to the zeroth Fox-Wolfram moment [7] must be less than 0.9. We further require that there be two high-energy photon candidates with an energy in the $\Upsilon(4S)$ rest frame between 1.5 and 3.5 GeV. At this point, all remaining pairs of photons are considered candidates for the decay $B^0 \to \gamma\gamma$. If the event contains more than one such B candidate all of them are kept for further analysis.

After this preselection, additional requirements are imposed on the $B^0 \to \gamma\gamma$ candidates. Photon bumps from the B candidate must not contain noisy crystals or crystals which produce no signals. The second moment of the energy distribution around the cluster's centroid must be smaller than 0.002. This value has been optimized to reject the remaining background from merged π^0 mesons.

Since B mesons at the $\Upsilon(4S)$ resonance are produced nearly at rest, the decay $B^0 \to \gamma\gamma$ will contain two nearly back-to-back photons with $E_\gamma^* \approx 2.6$ GeV in the $\Upsilon(4S)$ rest frame. This represents a clean signature and makes this channel relatively easy to study experimentally. We exploit this feature by considering only $B^0 \to \gamma\gamma$ candidates which have at least one photon with $2.3 < E_\gamma^* < 3.0$ GeV.

In order to reject photons from $\pi^0(\eta)$ decays we combine each photon from the B candidate with all the other photons in the event having energy greater than 50(250) MeV. The resulting $\pi^0(\eta)$ candidates are required to have an invariant mass beyond three standard deviations, or $3 \times 8.8(18)$ MeV$/c^2$, of the nominal $\pi^0(\eta)$ mass [8].

Reconstruction of exclusive final states from B mesons produced at the $\Upsilon(4\,S)$ resonance benefits from the beam energy constraint $E_B^* = E_b^*$. Thus, in the $\Upsilon(4S)$ rest frame the energies of the B meson decay products must add up to the beam energy. We calculate the energy difference $\Delta E \equiv E_{\gamma,1}^* + E_{\gamma,2}^* - E_b^*$ between the candidate B^0 meson and the beam energy in the $\Upsilon(4S)$ rest frame. The distribution of this quantity peaks at 0 GeV for true B mesons, and has a tail towards negative ΔE due to shower leakage in the EMC. The resolution in ΔE is obtained from signal Monte Carlo events with a fit of the ΔE distribution to an empirical function [9] and is $\sigma_{\Delta E} = 73$ MeV.

The B meson mass resolution is improved with the use of the beam energy constraint. We use the beam energy substituted mass $m_{\rm ES} \equiv \sqrt{E_b^{*2} - (\mathbf{p}_{\gamma,1}^* + \mathbf{p}_{\gamma,2}^*)^2}$. The resolution on $m_{\rm ES}$ is obtained from signal Monte Carlo events with a fit of the $m_{\rm ES}$ distribution to an empirical function [9] and is $\sigma_{m_{\rm ES}} = 3.9$ MeV$/c^2$.

For the purpose of determining numbers of events and efficiencies a rectangular signal region is defined. This region extends 2σ in ΔE about 0 MeV and extends 2σ in $m_{\rm ES}$ about the nominal mass m_{B^0} of the B^0 meson.

The search for $B^0 \to \gamma\gamma$ was performed as a blind analysis by hiding a 3σ region in ΔE and $m_{\rm ES}$ in on-resonance data until the development of the selection procedure was complete. This allows optimization of the selection and estimation of the background without the bias of knowing the number of events in the signal region.

Monte Carlo studies indicate that the main background arises from the process $e^+e^- \to q\overline{q}$ ($q = u, d, s$), referred to as a continuum background and modeled with the JETSET event generator [10]. Such events exhibit a two-jet structure and contain high-momentum, approximately back-to-back tracks. One source of background includes photons from initial-state radiation, others are photons from $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$ decays, where the decay is very asymmetric in the final-state photon energy. Background from merged π^0 mesons is negligible.

To reduce continuum background, we calculate the angle θ_T^* between one of the photons (chosen randomly) of the B^0 candidate and the thrust axis of the remaining tracks and neutral bumps in the event. The distribution of $|\cos\theta_T^*|$ is uniform for signal events and strongly peaked at 1 for continuum background events. We also calculate the angle θ_B^* between the momentum vector of the B^0 candidate and the beam axis in the $\Upsilon(4S)$ rest frame. The distribution of $|\cos\theta_B^*|$ is uniform for continuum background and follows a $\sin^2\theta_B^*$ distribution for signal events. The requirements for both $|\cos\theta_T^*|$ and $|\cos\theta_B^*|$ have been optimized to maximize the statistical significance $N_S/\sqrt{N_S + N_B}$, where N_S is the number of signal candidates expected, assuming for the branching fraction $\mathcal{B}(B^0 \to \gamma\gamma) = 1 \times 10^{-8}$ [1], and N_B is the expected number of background candidates determined from continuum Monte Carlo simulation and off-resonance data. We require $|\cos\theta_T^*| < 0.57$ and $|\cos\theta_B^*| < 0.81$. If more than one B meson candidate per event remains after this selection, which occurs in less than 0.1% of the events analyzed, we select the candidate with the smallest $|\Delta E|$. After all these selection criteria the overall efficiency for $B^0 \to \gamma\gamma$ decays is determined from the Monte Carlo simulation to be (10.7 ± 0.2)%, where the error is purely statistical. Table I shows the cumulative signal reconstruction efficiency as the selection criteria are applied.

A single event in the on-resonance data meets these selection criteria, as shown in Fig. 2. A number of exclusive decay modes that can mimic $B^0 \to \gamma\gamma$ decays have been studied with high statistics [equivalent to $(1.2\text{–}1.7) \times 10^4$ fb^{-1} assuming branching fractions of the order of 10^{-6}]. We expect negligible contributions from $B^0 \to \eta\eta$, $K^{*0}\gamma$, $\rho^0\gamma$, and $\pi^0\pi^0$, and a combined contribution of 0.7×10^{-3} events from $B^\pm \to \rho^\pm(\pi^\pm\pi^0)\gamma$ and $B^0 \to \omega(\pi^0\gamma)\gamma$. To further explore the question of the remaining background in the signal region, we define the *grand sideband* consisting of a rectangular region within the limits $-1.0 < \Delta E < 1.0$ GeV and $5.20 < m_{\rm ES} < 5.26$ GeV$/c^2$ (see Fig. 2, left dashed box). In this region we find a prediction of 34 ± 9 events from continuum Monte Carlo simulations, in good agreement with the observation of 43 ± 7 (44 ± 20) events from on-resonance data (off-resonance data of 2.2 fb^{-1} scaled to the full analyzed luminosity of 19.4 fb^{-1}). We parametrize the background using on-resonance data. The background in ΔE is parametrized in the grand sideband with a first order polynomial (see Fig. 3a); the background in $m_{\rm ES}$ is parametrized in the *lower sideband,* which is a rectangular region within the limits $-1.0 < \Delta E < -0.2$ GeV and $5.20 < m_{\rm ES} < 5.29$ GeV$/c^2$, with an empirical threshold function first employed by the ARGUS collaboration [11] (see Fig. 3b). Both parametrizations describe the corresponding distribution very well with a χ^2, normalized to

TABLE I. Cumulative signal reconstruction efficiency as selection criteria are applied. The first row shows the cumulative event selection efficiency. The additional rows give individual contributions to the B candidate selection efficiency. The cumulative signal reconstruction efficiency is given by the product of event selection and final B reconstruction efficiency.

Selection criteria	Efficiency [%]
Cumulative event preselection	39.8
Photon energy E_γ^*	92.9
Bump quality and second moment	86.8
π^0 and η veto	72.8
$\lvert\cos(\theta_B)\rvert$ and $\lvert\cos(\theta_T)\rvert$	40.1
Signal region	27.0
Cumulative	10.7

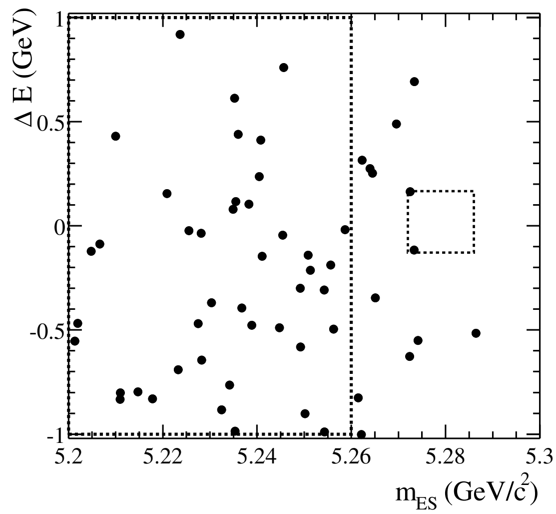

FIG. 2. Energy difference ΔE between the candidate B^0 meson and the beam energy in the $\Upsilon(4S)$ rest frame versus beam energy substituted mass m_{ES} for on-resonance data. We observe one event in the signal region, outlined as a black dashed box about $\Delta E = 0$ GeV, consistent with the expected background. The dashed box on the left shows the sideband used for background estimation.

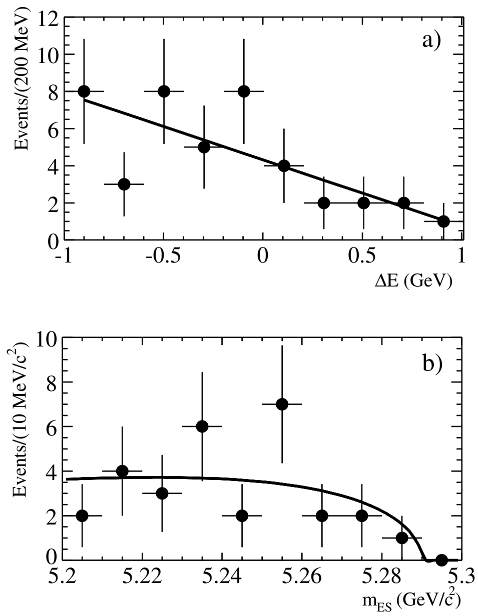

FIG. 3. (a) Fit to the ΔE distribution in the grand sideband to a first order polynomial; (b) fit of the m_{ES} distribution in the lower sideband with the ARGUS function [11]. See text for the definition of the sidebands.

the number of degrees of freedom, of about 0.8. Using this parametrization we are able to extrapolate the on-resonance grand sideband data into the signal region and find an expectation of $0.9^{+0.4}_{-0.3}$ events. This is consistent with the hypothesis that the observed event in the signal region is due to continuum background. Nevertheless, we choose to quote a conservative upper limit, assuming that the observed event in the signal region is in fact due to the decay $B^0 \to \gamma\gamma$. We use Poisson statistics to set an upper limit on the branching fraction. The upper limit on the branching fraction $\mathcal{B}$ is obtained from $\mathcal{B} = N_{\mathrm{UL}}/[\epsilon \cdot (N_{B^0} + N_{\overline{B}^0})]$, where N_{UL} is the upper limit on the number of observed events, ϵ is the signal reconstruction efficiency of $(10.7 \pm 0.2)\%$, and $N_{B^0} + N_{\overline{B}^0}$ is the number of produced B^0 and $\overline{B}^0$ mesons. $N_{B^0} + N_{\overline{B}^0}$ is equal to the number of $\Upsilon(4S)$ events since we assume the number of $B^0\overline{B}^0$ events to be 50% of the number of produced $\Upsilon(4S)$ events. This yields an upper limit on the branching fraction, based on statistics alone, of $\mathcal{B}(B^0 \to \gamma\gamma) < 1.7 \times 10^{-6}$ at the 90% confidence level.

Systematic effects arise from the modeling of the signal efficiency and the estimation of the number of B mesons in the data sample. A summary of all systematic errors is provided in Table II. The most significant sources are the photon detection efficiency and the ΔE selection due to the uncertainty in the photon energy scale and photon energy resolution. The systematic uncertainty on the photon detection efficiency has been determined from a study which compares the precisely known ratio [8] of the $\tau \to \pi\pi^0\nu_\tau$ and $\tau \to \pi\pi^0\pi^0\nu_\tau$ rates in Monte Carlo events and data. This uncertainty depends on the event multiplicity, whose effect is estimated by embedding photon bumps from radiative Bhabha events into both generic B meson data and generic B meson Monte Carlo events. The uncertainty in the energy scale is estimated with a study of symmetric $\eta \to \gamma\gamma$ decays, where both photons are within a narrow energy range. Systematic shifts of the reconstructed η mass from the nominal value measure the uncertainty in the energy scale in this energy range.

In order to include our systematic uncertainty in the determination of the upper limit, we follow a prescription given by [12]. The branching fraction $\mathcal{B}$ is calculated as $\mathcal{B} = n/S$, where n is the number of observed events and $S = 2.3 \times 10^6$ is the sensitivity, given by the product of the number of $B^0\overline{B}^0$ events and the overall $B^0 \to \gamma\gamma$ selection efficiency. Assuming a normal distribution for the uncertainty in $1/S$, the systematic uncertainty is accounted

TABLE II. Summary of systematic uncertainties on the signal efficiency and the number of produced $\Upsilon(4S)$ as an error on the branching fraction determination. The total systematic uncertainty is the sum of the individual contributions added in quadrature.

Systematic uncertainty	$(\Delta\mathcal{B}/\mathcal{B})\%$
Number of produced $\Upsilon(4S)$	1.6
Photon detection efficiency	6.5
η veto	2.0
π^0 veto	2.0
ΔE selection	5.3
m_{ES} selection	2.6
Track finding efficiency	1.8
Number of signal Monte Carlo events	2.0
Total	9.6

for by convoluting the Poisson probability distribution for the assumed branching fraction with a Gaussian error distribution for $1/S$. Our total systematic uncertainty of 9.6% included in this way has a negligible effect on the upper limit.

In summary, we performed a search for the decay $B^0 \to \gamma\gamma$. We observe one event in the signal region and infer an upper limit on the branching fraction of

$$\mathcal{B}(B^0 \to \gamma\gamma) < 1.7 \times 10^{-6}$$

at the 90% confidence level. This result improves the existing limit [3] by over a factor of 20.

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$$f(x) = N \times \begin{cases} \exp(-\frac{(x-\bar{x})^2}{2\sigma^2}), & (x-\bar{x})/\sigma > \alpha\,, \\ A \times (B - \frac{x-\bar{x}}{\sigma})^{-n}, & (x-\bar{x})/\sigma \le \alpha\,, \end{cases}$$
where $A \equiv (\frac{n}{|\alpha|})^n \times \exp(-|\alpha|^2/2)$ and $B \equiv \frac{n}{|\alpha|} - |\alpha|$. N is a normalization factor, $\bar{x}$ and σ are the fitted peak position and width of the Gaussian portion of the function, and α and n are the fitted point at which the function transitions to the power function and the exponent of the power function, respectively. D. Antreasyan, Crystal Ball Note No. 321, 1983.
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