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Search for the decay $B^0 \to J/\psi \gamma$


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RAPID COMMUNICATIONS

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SEARCH FOR THE DECAY $B^0 \rightarrow J/\psi \gamma$

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§Deceased.
Rare decays are sensitive probes of possible new physics effects beyond the standard model. The decay $B^0 \rightarrow J/\psi \gamma$ is a very rare decay, with a predicted branching fraction of $7.65 \times 10^{-9}$ [1]. The dominant mechanism is the exchange of a $W$ boson and the radiation of a photon from the light quark of the $B$ meson (Fig. 1). Possible new physics enhancements of the $B^0 \rightarrow J/\psi \gamma$ decay rate include a right-handed charged current or magnetic solenoid, which supplies a 1.5-T magnetic field.

We present the results of a search for the radiative decay $B^0 \rightarrow J/\psi \gamma$ in a data set containing $123.0 \times 10^6 Y(4S) \rightarrow B \bar{B}$ decays, collected by the BABAR detector at the PEP-II asymmetric-energy $e^+e^-$ storage ring at SLAC. We find no evidence for a signal and place an upper limit of $\mathcal{B}(B^0 \rightarrow J/\psi \gamma) < 1.6 \times 10^{-6}$ at 90% confidence level.

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Charge conjugation is implied throughout this paper.

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FIG. 1. Feynman diagram of the leading-order contribution to $B^0 \rightarrow J/\psi \gamma$. 

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than 0.5. We reconstruct a primary event vertex from the charged tracks and require that it be located within 6 cm of the beam spot in the direction parallel to the beam line, and within a transverse distance of 0.5 cm from the beam line. The beam spot rms size is approximately 0.9 cm in $z$, 120 $\mu$m horizontally, and 5.6 $\mu$m vertically. There must be at least three tracks in the fiducial volume satisfying the following criteria: they must have transverse momentum greater than 0.1 GeV/c, momentum smaller than 10 GeV/c, and at least 12 hits in the DCH; and they must approach within 10 cm of the beam spot in $z$ and within 1.5 cm of the beam line. Studies with simulated samples indicate that these criteria are satisfied by 96% of $Y(4S) \rightarrow B \bar{B}$ decays.

Candidate $B^0 \rightarrow J/\psi \gamma$ decays are reconstructed as follows. A $B^0$ candidate is formed from a $J/\psi$ and a photon candidate. The $J/\psi$ candidate is reconstructed in the low-background, high-efficiency $J/\psi \rightarrow \ell^+ \ell^-$ mode only. Electron candidates are identified using the ratio of calorimeter energy to track momentum ($E/p$), the ionization loss in the tracking system (dE/dx), and the shape of the shower in the calorimeter. Whenever possible, photons radiated by an electron traversing material prior to the DCH (0.04 radiation lengths at normal incidence) are combined with the track. These bremsstrahlung-photon candidates are characterized by an EMC energy greater than 30 MeV and a polar angle within 35 mrad of the electron direction, as well as an azimuthal angle either within 50 mrad of the electron direction, or between the electron direction at the origin and the azimuth of the impact point in the EMC. Muons are identified by the energy deposited in the EMC, the compatibility of the track formed by the hits in the IFR with the extrapolation of a track measured in the DCH, and the amount of iron penetrated by this track. Studies of data-derived control samples show that at a typical lepton momentum of 2 GeV/c, the efficiency of the electron (muon) identification criteria is 93% (83%), with a pion misidentification probability of 0.2% (8%). Photons are neutral candidates with characteristic electromagnetic shower shapes in the EMC. To determine the photon direction, we assume that the photon candidate originates at the $J/\psi \rightarrow \ell^+ \ell^-$ vertex.

We use the simulated samples to derive an optimized set of selection criteria for $B^0 \rightarrow J/\psi \gamma$ events. For the optimization we minimize the ratio $\sqrt{\nu_0/\nu_s}$, where $\nu_b$ and $\nu_s$ are the respective efficiencies for background and signal events to pass the selection criteria. The optimized selection criteria are described below and summarized in Table I.

To identify and select $B$ candidates we use the kinematic variables $\Delta E$ and $m_{ES}$. The energy difference $\Delta E$ is given by $\Delta E = (s/2 + p_Y \cdot q_B - s)/2\sqrt{s}$, where $q_Y = (E_Y, p_Y)$ is the four-momentum of the $Y(4S)$ as determined from beam parameters, $q_B = q_{J/\psi} + q_\gamma = (E_B, \vec{p}_B)$ is the reconstructed four-momentum of the $B$ candidate, and $s = q_Y^2$ is the squared center-of-mass energy. The energy-substituted mass $m_{ES}$ is given by $m_{ES} = \sqrt{(s/2 + \vec{p}_Y \cdot \vec{p}_B)^2/E_Y^2 - |\vec{p}_B|^2}$. The advantage of using $\Delta E$ and $m_{ES}$ to impose the kinematic constraints for $B$ decays is that these quantities are largely uncorrelated and make maximum use of the well-determined beam four-momenta. For the optimization and background studies we use only events that fall within the ``analysis window'' defined by $5.2 < m_{ES} < 5.3$ GeV/$c^2$ and $|\Delta E| < 0.30$ GeV; this defines the range of the histograms in Fig. 2. A perfectly reconstructed $B^0 \rightarrow J/\psi \gamma$ decay should have $\Delta E = 0$ and $m_{ES} = m_B$. Therefore we demand that $B^0 \rightarrow J/\psi \gamma$ candidates fall within the ``signal region'' in the $\Delta E$ vs $m_{ES}$ plane defined by $5.270 < m_{ES} < 5.290$ GeV/$c^2$ and $-0.05 < \Delta E < 0.08$ GeV. In Fig. 2, the signal region is indicated by a box.

We reject continuum background using a number of topological variables to distinguish between continuum events, which tend to be highly directional, and $B$-decay events, which tend to be spherically symmetric. We determine the thrust and sphericity axes of the particles not used to reconstruct the $B$ candidate, and demand that the angle $\theta_t$ ($\theta_{sph}$) between the thrust (sphericity) axis of these particles and the thrust (sphericity) axis of the $B$ candidate satisfy $|\cos \theta_t| < 0.75$ ($|\cos \theta_{sph}| < 0.85$). In $Y(4S) \rightarrow B \bar{B}$ decays, the angle $\theta_B$ between the beam direction and the flight direction of the $B$ candidate in the $e^+ e^-$ center-of-mass frame follows a $\sin^2 \theta_B$ distribution. We require that this angle satisfy $|\cos \theta_B| < 0.90$. Finally, we also tighten the $R_2$ requirement to $R_2 < 0.45$. Studies both of simulated background and off-peak data indicate that the fraction of continuum events satisfying these criteria is negligible.

We reject background from $B$ decays using $J/\psi$ and photon selection criteria. For the $J/\psi$ selection, the invariant mass of the $\ell^+ \ell^-$ pair of the reconstructed $J/\psi \rightarrow \ell^+ \ell^-$ decay is required to fall close to that

<table>
<thead>
<tr>
<th>Variable</th>
<th>Requirement</th>
</tr>
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<tbody>
<tr>
<td>$J/\psi$ mass</td>
<td>$3.06 &lt; m(e^+ e^-) &lt; 3.12$ GeV/$c^2$</td>
</tr>
<tr>
<td></td>
<td>$3.07 &lt; m(\mu^+ \mu^-) &lt; 3.13$ GeV/$c^2$</td>
</tr>
<tr>
<td>photon LAT</td>
<td>$LAT &lt; 0.35$</td>
</tr>
<tr>
<td>photon angle</td>
<td>$\cos \theta_\gamma &gt; -0.35$</td>
</tr>
<tr>
<td>$x^0$ veto</td>
<td>reject $0.115 &lt; m_{pair} &lt; 0.155$ GeV/$c^2$</td>
</tr>
<tr>
<td>Fox-Wolfram moment</td>
<td>$R_2 &lt; 0.45$</td>
</tr>
<tr>
<td>thrust angle</td>
<td>$</td>
</tr>
<tr>
<td>sphericity angle</td>
<td>$</td>
</tr>
<tr>
<td>$B$ polar angle</td>
<td>$</td>
</tr>
<tr>
<td>signal region</td>
<td>$5.270 &lt; m_{ES} &lt; 5.290$ GeV/$c^2$</td>
</tr>
<tr>
<td></td>
<td>$-0.05 &lt; \Delta E &lt; 0.08$ GeV</td>
</tr>
</tbody>
</table>

TABLE I. The selection criteria.
of the known $J/\psi$ mass [5]: $3.06 < m(e^+e^-) < 3.12 \text{ GeV}/c^2$ for $J/\psi \to e^+e^-$ candidates and $3.07 < m(\mu^+\mu^-) < 3.13 \text{ GeV}/c^2$ for $J/\psi \to \mu^+\mu^-$ candidates. We require that photon candidates satisfy $\text{LAT} < 0.35$, where $\text{LAT}$ [6] is a shower-shape variable used to distinguish between electromagnetic and hadronic showers. In addition, we require the photon direction to satisfy $\cos\theta_\gamma > -0.35$.

The main source of photons in BABAR is the decay of neutral pions, so we apply a veto to reject photons from $\pi^0 \to \gamma\gamma$ decays. We reject events in which the $B^0 \to J/\psi\gamma$ photon candidate combined with any other photon candidate forms a pair with an invariant mass within 20 MeV/$c^2$ of the neutral pion mass [5].

The signal efficiency of the optimized selection is estimated from the simulations to be $\varepsilon_s = 0.102 \pm 0.010$.

Of interest in the background studies are the events that pass all of the selection criteria except for the requirement to fall within the signal region [Fig. 2 (c)]. Most of this background is concentrated in the low-$\Delta E$ region of the $\Delta E$-$m_{ES}$ plane. The asymmetry of the signal region in $\Delta E$ ensures that the majority of these events fall outside of the signal region. The small fraction of this background in the signal region is due primarily to $B^0 \to J/\psi\pi^0$ decays in which a photon from $\pi^0 \to \gamma\gamma$ is misidentified as a $B^0 \to J/\psi\gamma$ photon. This usually occurs when the other photon in the reconstruction falls below the 30 MeV energy threshold. There is also background from $B^0 \to J/\psi K_s^0$ decays, due to $K_s^0 \to 3\pi^0$ decays in the EMC for which the six resulting showers overlap and are incorrectly interpreted as a shower from a single photon.

We estimate the background using a large simulated sample distinct from that used to optimize the selection criteria. Each event in this sample contains either a $B \to J/\psi\pi^0$ or a $B \to J/\psi K_s^0$ decay. After normalizing to the data luminosity we obtain background estimates of $0.59$ in the $B \to J/\psi\pi^0$ mode and $0.12$ in the $B \to J/\psi K_s^0$ mode, resulting in a total background estimate of $n_b = 0.71 \pm 0.31$ events. The contributions to the uncertainty are discussed below.

To validate the simulated-background modeling we perform several cross-checks. We compare background estimates from simulations and from on-peak data, outside the signal region but in the analysis window. The results are consistent both when the estimates are obtained with all of the selection criteria applied, and when the estimates are obtained with all of the criteria applied except for the pion veto. In addition, we compare the background estimates from off-peak data and from simulated continuum background in the full analysis window. In both cases, no events pass the selection criteria.

The relative systematic errors in the signal efficiency and in the background estimate are presented in Table II. For both $\varepsilon_s$ and $n_b$ there is statistical uncertainty in the number of events passing the selection. The uncertainty in the background estimate also includes uncertainty from the number of $Y(4S)$ in the data set, $N_{Y(4S)} = (123.3 \pm 1.4) \times 10^6$, and the uncertainty in the following branching fractions. $\mathcal{B}(B^0 \to J/\psi\pi^0)$ and $\mathcal{B}(B^0 \to J/\psi K_s^0)$ are obtained from Ref. [5]. $\mathcal{B}(J/\psi \to \ell^+\ell^-) = 0.1181 \pm 0.0020$ is the sum of the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ branching fractions [5] assuming fully correlated uncertainties. $\mathcal{B}[Y(4S) \to B^0\overline{B}^0] = 0.499 \pm 0.012$ is determined from Ref. [7] assuming that the $Y(4S)$ decays 100% to $B\overline{B}$.

In addition, we correct for differences between simulations and data, and each of these corrections contributes to the systematic uncertainty. The required corrections for tracking, lepton-identification, and photon-reconstruction efficiencies are derived from independent studies comparing the results from simulations with those from data control samples. Also, comparison of the $\Delta E$ distribution of $B^0 \to K^{*0}\gamma$ decays in real and simulated samples reveals a difference of about 28 MeV in the central value for $\Delta E$ between data and Monte Carlo. This effect is due to imperfect simulation of photon energy loss in the detector. $B^0 \to J/\psi\gamma$ is topologically similar to $B^0 \to K^{*0}\gamma$ but has a lower photon energy, so we apply a correction of $(22 \pm 10)$ MeV to $\Delta E$ in the simulated samples. As shown in Table II, this $\Delta E$ correction is the largest contribution to the uncertainty in the background estimate $n_b$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>$n_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$ correction</td>
<td>7.6</td>
<td>33</td>
</tr>
<tr>
<td>Tracking</td>
<td>4.0</td>
<td>3.4</td>
</tr>
<tr>
<td>Lepton ID</td>
<td>3.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Neutral ID</td>
<td>2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>Statistics (simulated samples)</td>
<td>1.5</td>
<td>24</td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \to J/\psi\pi^0)$, $\mathcal{B}(B^0 \to J/\psi K_s^0)$</td>
<td>N/A</td>
<td>15</td>
</tr>
<tr>
<td>$\mathcal{B}(J/\psi \to \ell^+\ell^-)$, and $\mathcal{B}[Y(4S) \to B^0\overline{B}^0]$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9.8</td>
<td>44</td>
</tr>
</tbody>
</table>
tion leads to the largest systematic error in both the efficiency and the background calculation.

No events in the signal region satisfy the final selection criteria [Fig. 2(a)]. The probability of observing 0 events when expecting a background of 0.71 events is 49%. In the analysis window we observe 10 events in data, consistent at the 8% level with the expected background of $5.7 \pm 1.0$ events.

We determine the upper limit on the branching fraction $\mathcal{B}(B^0 \to J/\psi\gamma)$ by performing a Bayesian analysis with a uniform prior above zero. We define the likelihood for $\mathcal{B}(B^0 \to J/\psi\gamma)$ as the probability that exactly zero events pass the selection, given that the mean expected number of observed events is

$$\mu = n_b + N_{B^0} \varepsilon_s \mathcal{B}(J/\psi \to \ell^+ \ell^-) \mathcal{B}(B^0 \to J/\psi\gamma),$$

where $N_{B^0} = 2 N_{Y(4S)} \mathcal{B}[Y(4S) \to B^0\overline{B}^0]$ is the number of $B^0$ mesons in the data set. The analysis takes into account the uncertainties in $\varepsilon_s$ and $n_b$. The 90% confidence level upper limit, defined as the branching fraction value that separates the lower 90% of the area under the likelihood function curve from the upper 10%, is $\mathcal{B}(B^0 \to J/\psi\gamma) < 1.6 \times 10^{-6}$. This limit is dominated by statistical errors; in the absence of systematic errors, it would improve by less than $0.1 \times 10^{-6}$.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), Institute of High-Energy Physics (China), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from CONACyT (Mexico), the A.P. Sloan Foundation, the Research Corporation, and the Alexander von Humboldt Foundation.