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# Search for the rare decay $\overline{B}^0 \to D^{*0}\gamma$

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We report on a search for the rare decay $\overline{B}^0 \to D^{*0}\gamma$, which in the standard model is dominated by $W$-exchange. The analysis is based on a data sample comprising $87.8 \times 10^6$ $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II asymmetric-energy $B$ Factory at SLAC. No significant signal is observed, and an upper limit on the branching fraction of $2.5 \times 10^{-5}$ at the 90% confidence level is obtained.

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Within the standard model (SM), the rare decay $\overline{B}^0 \to D^{*0}\gamma$ [1] is dominated by the $W$-boson exchange process. One of the leading SM contributions to the decay is illustrated in Fig. 1. Similar $W$-exchange transitions are present in other decays. For example, they contribute to the decay $B^0 \to \rho^0\gamma$ along with the leading electromagnetic-penguin process [2]. The branching fraction $\mathcal{B}(\overline{B}^0 \to D^{*0}\gamma)$ is estimated to be of order $10^{-6}$ [2–4], but the presence of a large $q\overline{q}g$ (color octet) component in the wave function of the $B$ meson may reduce the color-suppression enough to raise the branching fraction by a factor of about 10 [4]. A search for $\overline{B}^0 \to D^{*0}\gamma$, published by the CLEO collaboration [5], resulted in a limit of $\mathcal{B}(\overline{B}^0 \to D^{*0}\gamma) < 5.0 \times 10^{-5}$ at the 90% confidence level (C.L.).

We search for the decay $\overline{B}^0 \to D^{*0}\gamma$ in data collected using the *BABAR* detector operating at the Stanford Linear Accelerator Center (SLAC) PEP-II asymmetric-energy $e^+e^-$ collider. The collider runs with a center-of-mass (CM) energy of 10.58 GeV at the peak of the $\Upsilon(4S)$ resonance, which decays into $B^+B^-$ and $B^0\overline{B}^0$ pairs. The analysis is based on $87.8 \times 10^6$ $B\overline{B}$ pairs, corresponding to an integrated luminosity of 79.9 fb$^{-1}$. The *BABAR* detector is described in detail in Ref. [6]; here we introduce briefly the detector systems important for the present analysis. Tracks of charged particles and their momenta are measured in a vertex tracker, consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer drift chamber. Both systems are located within a 1.5-T solenoidal magnetic field and provide $\mathrm{d}E/\mathrm{d}x$ measurements for particle identification (PID). A Cherenkov ring imaging detector adds measurements for PID by recording Cherenkov light emitted from charged particles traversing transparent quartz bars. Photons are identified by an electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals.

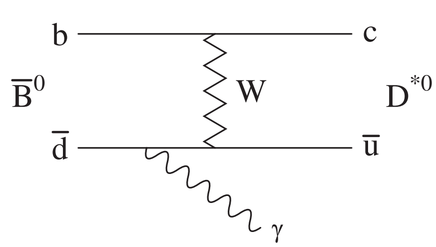


FIG. 1. $W$-exchange is the leading contribution to the $\overline{B}^0 \to D^{*0}\gamma$ decay in the standard model. The photon may be emitted from any quark line or the $W$.

Event samples from Monte Carlo (MC) simulations are used to optimize the event selection criteria and to estimate the signal efficiency and background. The detector response is simulated using GEANT4 [7]. The MC sample for the signal $\overline{B}^0 \to D^{*0}\gamma$ contains 328 000 events. We use MC samples of similar size for several exclusive $B$-decay background modes. The color-suppressed hadronic decay $\overline{B}^0 \to D^{*0}\pi^0$, with branching fraction $(2.7 \pm 0.5)\times 10^{-4}$ [8], is the largest contributor among them. Other backgrounds originate from $B\overline{B}$ modes with incompletely or incorrectly reconstructed particles, and from random combinations of particles from two different $B$ mesons or from $q\overline{q}$ pairs. For these, we use MC samples of generic $B\overline{B}$ events and continuum $q\overline{q}$ ($q = u, d, s, c$) events corresponding to about 200 fb$^{-1}$ and 110 fb$^{-1}$, respectively.

The $D^{*0}$ candidates are reconstructed in six submodes, with $D^{*0} \to D^0(\pi^0, \gamma)$ and $D^0 \to (K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-)$. The event selection criteria are optimized by using the MC samples to maximize $S^2/(S+B)$, where $S$ ($B$) is the number of signal (background) events. A signal branching fraction of $10^{-6}$ is assumed during the optimization. The most important selection requirements are described below.

The photon from the decay $\overline{B}^0 \to D^{*0}\gamma$ is emitted with an energy of about 2.3 GeV in the CM frame ("hard photon"). Although this high energy leads to a relatively clear signal, care must be taken that remnants of $\pi^0$ decays are not mistaken as the signal photon. The "$\pi^0$ veto" rejects a hard photon candidate if its combination with any other photon with laboratory energy larger than 30 MeV yields an invariant mass in the range $[110, 155]$ MeV$/c^2$. A similar veto for $\eta$ decays rejects a photon candidate if its combination with any other photon of laboratory energy larger than 250 MeV yields an invariant mass within $[508, 588]$ MeV$/c^2$. Hard photon candidates must also pass a calorimeter shower-shape requirement designed to exclude irregularly shaped showers caused, for example, by overlapping photons from $\pi^0$ decay. Background is further suppressed by requiring a hard photon candidate to be isolated from all other showers and tracks by at least 50 cm in the calorimeter.

A photon candidate from the decay $D^{*0} \to D^0\gamma$ ("soft photon") must satisfy the same shower-shape requirement and $\eta$ veto that are applied to hard photons. In the $\pi^0$ veto the minimum energy for the other photon is raised to 80 MeV and the invariant mass range is restricted to $[115, 150]$ MeV/$c^2$. In addition, the CM energy of the soft photon candidate has to be at least 110 MeV.

The mass of the $\pi^0$ in the decay $D^{*0} \rightarrow D^0\pi^0$ and of the $\pi^0$ in the decay $D^0 \rightarrow K^-\pi^+\pi^0$ is required to be within 11 MeV/$c^2$ of the true $\pi^0$ mass (which corresponds to a cut at about $1.7\sigma$, where $\sigma$ is the $\pi^0$ mass resolution). Photons from $\pi^0$ decay need a minimum energy of 30 MeV and have to pass a similar, but slightly less stringent, shower-shape requirement as the hard and soft photons.

The charged $K$ and $\pi$ tracks are required to originate from the interaction point and have to pass likelihood-based particle identification selections using d$E$/d$x$ and Cherenkov light measurements. The $K$ track in the $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decay is in addition required to have a transverse momentum larger than 0.1 GeV/$c$ and at least 12 hits in the drift chamber. A vertex fit is applied to the $D^0$ candidates. They are required to have masses close to the known $D^0$ mass: within 12 MeV/$c^2$ ($\sim 1.8\sigma$) for $D^0 \rightarrow K^-\pi^+$, within 23 MeV/$c^2$ ($\sim 1.9\sigma$) for $D^0 \rightarrow K^-\pi^+\pi^0$, and within 12 MeV/$c^2$ ($\sim 2.3\sigma$) for $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$. Additional selection requirements are applied to $D^0$ candidates decaying into $K^-\pi^+\pi^0$. The laboratory energy of the $\pi^0$ must be at least 250 MeV, and only $D^0 \rightarrow K^-\pi^+\pi^0$ candidates that appear in the Dalitz plot close to known resonances [9] are accepted. The difference between the $D^{*0}$ and $D^0$ mass has to be within 2 MeV/$c^2$ ($\sim 2\sigma$) for $D^{*0} \rightarrow D^0\pi^0$ and within 9 MeV/$c^2$ ($\sim 1.8\sigma$) for $D^{*0} \rightarrow D^0\gamma$ of the known value of Ref. [8].

The $D^{*0}$ helicity angle $\theta_H^*$ is defined in the $D^{*0}$ CM frame as the angle between the direction of the $D^0$ and the direction opposite to the $B$ momentum. For the $D^{*0} \rightarrow D^0\pi^0$ modes, $\cos\theta_H^*$ is distributed as $\sin^2\theta_H^*$ for signal, but as $\cos^2\theta_H^*$ for background from $\overline{B}^0 \rightarrow D^{*0}\pi^0$. Optimization leads to the requirement $|\cos\theta_H^*| < 0.75$. No such condition is imposed for $D^{*0} \rightarrow D^0\gamma$ modes.

Several selection requirements reduce the number of fake decays from $q\overline{q}$ continuum background. The angle $\theta_B^*$ is defined as the angle between the $B$ candidate momentum in the $\Upsilon(4S)$ CM frame and the beam axis. In $q\overline{q}$ background events the distribution is uniform in $\cos\theta_B^*$, while for real $B$ mesons it follows a $\sin^2\theta_B^*$ distribution. We require that $|\cos\theta_B^*| < 0.8$. The angle $\theta_T^*$ is the angle between the thrust direction of the $B$ candidate and the thrust direction computed from the other photons and tracks in the event. For signal events the distribution of $|\cos\theta_T^*|$ is flat, while for continuum events the distribution has a maximum at $|\cos\theta_T^*| = 1$ due to their jetlike nature. We require that $|\cos\theta_T^*| < 0.75$.

The candidates are subsequently characterized with two kinematic quantities, $m_{\rm ES}$ and $\Delta E$. For the "energy-substituted mass" $m_{\rm ES}$, the energy of the $B$ candidate is substituted by precisely known beam parameters:

$$m_{\rm ES} = \sqrt{(s/2 + c^2\mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - c^2\mathbf{p}_B^2}, \quad (1)$$

where $s$ is the square of the total CM energy, $E_0$ and $\mathbf{p}_0$ are the energy and momentum of the initial $\Upsilon(4S)$ in the laboratory frame, and $\mathbf{p}_B = \mathbf{p}_{D^{*0}} + \mathbf{p}_\gamma$ is the momentum of the $B$ candidate, also taken in the laboratory frame. The quantity $\Delta E$ is defined as the difference between the energy of the $B$ candidate $E^*$ and the beam energy, both taken in the CM system:

$$\Delta E = E^* - \frac{1}{2}\sqrt{s}. \quad (2)$$

Requirements of $|\Delta E| < 0.34$ GeV and $5.2 < m_{\rm ES} < 5.29$ GeV/$c^2$ are applied at this point.

If an event contains more than one $\overline{B}^0 \rightarrow D^{*0}\gamma$ candidate passing all selection criteria, the selection is made based on a $\chi^2$ function that uses the measured $D^0$ mass and $D^{*0}$-$D^0$ mass difference, the measured resolutions, and known mass and mass-difference values from Ref. [8]. This selection is sufficient, as the ambiguity is never due to the presence of two hard photon candidates.

The distribution of $m_{\rm ES}$ versus $\Delta E$ is shown in Fig. 2 for the data taken at the $\Upsilon(4S)$ resonance. While the combinatorial $q\overline{q}$ background is smoothly distributed over this plane, the signal should peak around $\Delta E = 0$ and $m_{\rm ES} = 5.28$ GeV/$c^2$. The borders of the signal box are given by $5.275 < m_{\rm ES} < 5.285$ GeV/$c^2$ and $-0.1 < \Delta E < 0.08$ GeV, extending to about 1.7 (1.9) times the resolution of $m_{\rm ES}$ ($\Delta E$) of signal events. The $\Delta E$ constraint is asymmetric to account for the energy leakage from the calorimeter for the hard photon candidates. The area with $m_{\rm ES}$ ranging from 5.2 GeV/$c^2$ to 5.27 GeV/$c^2$ is called the "grand sideband."

The contributions to the systematic uncertainties in the signal reconstruction efficiencies are listed in Table I. The overall relative uncertainties range from 16.5% to 19.8%, depending on the reconstruction mode (see Table II). The

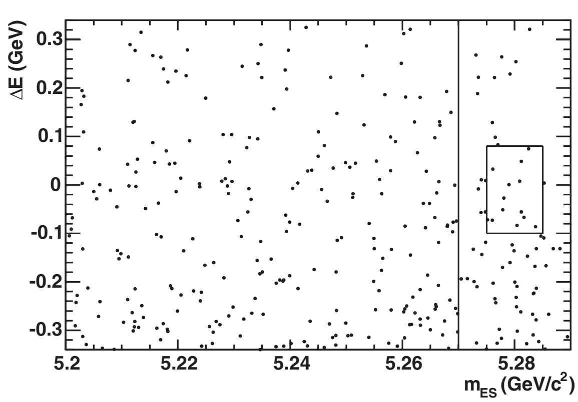


FIG. 2. Distribution of data events in the $\Delta E$-$m_{\rm ES}$ plane. The lines indicate the regions of the signal box and of the grand sideband.

TABLE I. Maximal and minimal relative systematic uncertainties in the efficiency for the individual reconstruction modes.

| | Systematic uncertainty in % of the efficiency |
|---|---|
| $\gamma$ and $\pi^0$ reconstruction | 5.0 to 12.5 |
| Hard $\gamma$ separation | 2.0 |
| Shower shape | 1.0 to 2.5 |
| $\pi^0$, $\eta$ veto | 1.5 to 3.0 |
| Track finding efficiency | 2.6 to 5.9 |
| Kaon PID | 3.0 |
| $D^0$ mass | 2.3 to 4.4 |
| $D^{*0}$-$D^0$ mass difference | 2.5 to 6.7 |
| Dalitz structure | 0.0 to 5.0 |
| Helicity angle $\theta^*_H$ | 0.0 to 3.8 |
| Thrust angle $\theta^*_T$ | 5.5 to 7.3 |
| $B^0$ angle $\theta^*_B$ | 3.0 to 3.8 |
| $\Delta E$ | 8.6 to 12.0 |
| $m_{ES}$ | 2.3 to 4.0 |
| Simulation statistics | 2.0 to 4.7 |
| Sum | 16.5 to 19.8 |

major contributors are described here in more detail. The uncertainties in the photon reconstruction due to efficiency, energy scale, and energy resolution uncertainties are studied with control samples and result in an uncertainty of 2.5% per photon (5% per $\pi^0$). Studies of the track finding efficiency using control samples result in uncertainties of 2.6% to 5.9% depending on the mode. The size of the uncertainty in the $\Delta E$ and $m_{ES}$ selection is obtained by varying the selection according to observed differences between data and MC simulation. For the thrust angle $\theta^*_T$, the $B^0$ angle $\theta^*_B$, and the helicity angle $\theta^*_H$, the size of the uncertainties is obtained by shifting the selection requirement by $\pm 0.05$ in the cosine of each angle. The uncertainty due to possible discrepancies between data and MC simulation in the $D^0$ mass and the $D^{*0}$-$D^0$ mass difference is estimated by comparing these distributions for events in the grand sideband. Data and Monte Carlo simulation agree sufficiently well, and the size of the systematic uncertainty in the efficiency is obtained from the uncertainty on the fits to the mass and mass-difference plots.

Several correction factors are applied to the signal efficiency based on comparison studies on data and Monte Carlo simulations: a tracking efficiency factor of 0.992 for the kaon in the decay $D^0 \to K^-\pi^+\pi^+\pi^-$, a factor 0.95 for the decay $D^0 \to K^-\pi^+\pi^0$ due to the selection requirement involving the Dalitz structure, and factors from 0.89 to 0.95 depending on the reconstructed mode due to photon reconstruction. The overall selection efficiencies for the six signal modes are listed in Table II. The uncertainties on the efficiencies include all contributions from systematic effects on the efficiencies. The combined efficiency (weighted by the branching fractions of the individual modes and taking correlations in the uncertainties between the six submodes into account) is $(1.8 \pm 0.3)\%$. In the determination of the $\overline{B}^0 \to D^{*0}\gamma$ branching fraction results, a 1.1% uncertainty on the number of $B\overline{B}$ pairs in the data sample is included as well as the contribution by the $D^0$ ($D^{*0}$) branching fraction uncertainties [8].

The number of events expected in the signal box due to background is not estimated from data, but from MC simulation, since the $\Delta E$-$m_{ES}$ distributions of several categories of $B\overline{B}$ background peak inside the signal box. After counting the MC events and scaling the number to 79.9 fb$^{-1}$, a total of $9.4 \pm 1.7$ background events is expected for all six modes combined. Of those, 2.9 events originate from $\overline{B}^0 \to D^{*0}\pi^0$, 5.1 events from other $B\overline{B}$ decays, and 1.4 events from $q\overline{q}$ events. The breakdown for each channel is given in Table II.

The estimate of the number of background events is cross-checked by two studies, one based on events in the grand sideband, and the other based on events in the signal box using a control sample of $D^{*0}\pi^0$ events. The first study results in ratios of data-to-MC events ranging from $1.0 \pm 0.3$ to $1.5 \pm 0.2$ for the various $D^{*0}$ decay modes, and a ratio of $1.2 \pm 0.1$ for all modes combined. Taking the

TABLE II. Results for individual modes and all modes combined. The upper limit is given for 90% C.L.

| Mode | Branching fraction of mode [8] (in %) | Relative systematic uncertainty (in %) | Signal efficiency (in %) | Expected background (events) | Range of data-to-MC ratios | Observed in signal box (events) | Branching fraction upper limit ($\times 10^{-5}$) |
|---|---|---|---|---|---|---|---|
| $D^{*0} \to D^0\pi^0$ | | | | | | | |
| $D^0 \to K^-\pi^+$ | 2.3 | 16.5 | $4.2 \pm 0.7$ | $1.5 \pm 0.7$ | 0.0 to 1.6 | 1 | 3.4 |
| $D^0 \to K^-\pi^+\pi^0$ | 7.9 | 19.8 | $1.2 \pm 0.2$ | $2.0 \pm 0.8$ | 0.0 to 1.3 | 1 | 3.5 |
| $D^0 \to K^-\pi^+\pi^+\pi^-$ | 4.6 | 17.3 | $2.0 \pm 0.3$ | $0.7 \pm 0.1$ | 0.5 to 2.0 | 1 | 3.9 |
| $D^{*0} \to D^0\gamma$ | | | | | | | |
| $D^0 \to K^-\pi^+$ | 1.4 | 17.3 | $3.8 \pm 0.7$ | $1.6 \pm 0.4$ | 0.4 to 1.6 | 2 | 8.0 |
| $D^0 \to K^-\pi^+\pi^0$ | 4.9 | 19.6 | $0.9 \pm 0.2$ | $2.4 \pm 1.2$ | 0.1 to 1.2 | 3 | 14.8 |
| $D^0 \to K^-\pi^+\pi^+\pi^-$ | 2.8 | 17.7 | $1.7 \pm 0.3$ | $1.2 \pm 0.2$ | 0.2 to 1.7 | 5 | 20.3 |
| All modes combined | 23.9 | 16.8 | $1.8 \pm 0.3$ | $9.4 \pm 1.7$ | 0.4 to 1.3 | 13 | 2.5 |

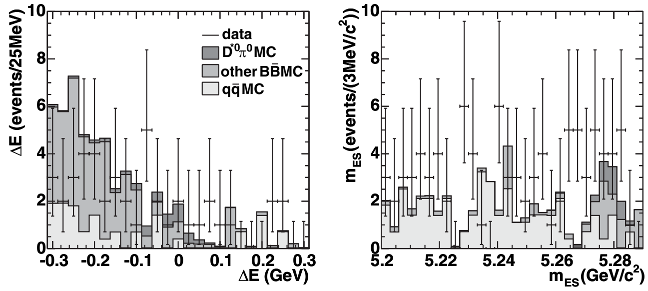


FIG. 3. $\Delta E$ (left) and $m_{\rm ES}$ (right) distributions for data (points) and MC simulation (shaded histograms). All selection requirements are applied including the $m_{\rm ES}$ signal box requirement for the left plot and the $\Delta E$ signal box requirement for the right plot.

uncertainties into account, data and MC simulation do not disagree significantly. For the second study, $\overline{B}^0 \to D^{*0}\pi^0$ events are selected by loosening some selection requirements and by inverting the $\pi^0$ veto: we now keep events in which a photon combined with the hard photon forms a reasonable $\pi^0$ candidate. The number of events seen in the signal box is usually found to be lower in data than in MC simulation with data-to-MC ratios from $0.3 \pm 0.3$ to $1.2 \pm 0.7$ for the various $D^{*0}$ decay modes and $0.6 \pm 0.2$ for all modes combined.

We observe 13 events in the signal box. Figure 3 presents the $\Delta E$ and $m_{\rm ES}$ distributions with all selection requirements applied. The Monte Carlo simulation is shown with separate contributions from $\overline{B}^0 \to D^{*0}\pi^0$, other $B\overline{B}$, and $q\overline{q}$ events.

The branching fractions are determined in a frequentist-model approach, modified based on Ref. [10]. Besides taking the systematic uncertainty in the efficiency and the statistical uncertainty in the background estimate into account, the background expectation value is also shifted by a factor selected from a flat distribution of the range determined by the data-to-Monte Carlo ratios (see Table II). When combining all six modes, this shift comes from the range 0.4 to 1.3 (derived from $0.6 \pm 0.2$ and $1.2 \pm 0.1$) and is applied coherently for each of the modes.

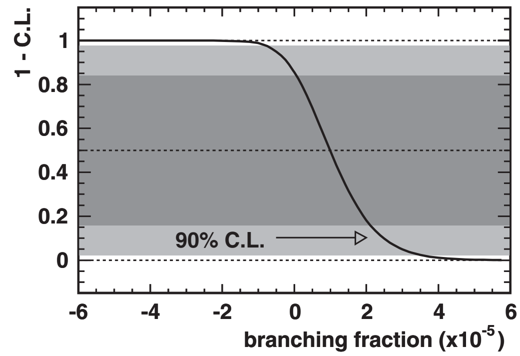


FIG. 4. $1 -$ confidence level versus the assumed branching fraction. The shaded areas are the 68% and 95% probability regions. The 90% C.L. is marked with an arrow.

We assume that 50% of the $\Upsilon(4S)$ mesons decay into neutral $B\overline{B}$ pairs. Figure 4 displays $1 -$ C.L. versus the assumed branching fraction. The significance of this measurement, i.e., $1 -$ C.L. at branching fraction zero, is 0.86. The central value of the branching fraction of $\overline{B}^0 \to D^{*0}\gamma$ is $(1.0^{+1.1}_{-0.9}) \times 10^{-5}$, which is consistent with zero. The upper limit on the branching fraction is $\mathcal{B}(\overline{B}^0 \to D^{*0}\gamma) < 2.5 \times 10^{-5}$ at 90% confidence level and is in agreement with the theoretical expectations.

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