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Search for the Decay $B^0 \to p\bar{p}$

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We present the result of a search for the charmless two-body baryonic decay $B^0 \to p\bar{p}$ in a sample of 88 million $\Upsilon(4S) \to B\bar{B}$ decays collected by the BaBar detector at the SLAC PEP-II asymmetric-energy B Factory. We use Cherenkov radiation to identify protons cleanly, and determine the signal yield with a maximum-likelihood fit technique using kinematic and topological information. We find no evidence for a signal and place a 90% confidence-level upper limit of $\mathcal{B}(B^0 \to p\bar{p}) < 2.7 \times 10^{-7}$.

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We report the result of a search for the charmless two-body baryonic decay $B^0 \to p\bar{p}$ [1]. Although B mesons have recently been observed to decay into several charmless three-body baryonic final states [2], there is currently no evidence for the corresponding charmless two-body decays. Previous searches [3, 4] for $B^0 \to p\bar{p}$ decays have yielded upper limits on the branching fraction at the level of 10^{-6}, which is consistent with calculations based on QCD sum rules [5] and the pole model [6]. A simple scaling of the measured branching fraction for $B^0 \to \Lambda_c^- p$ [7] by the current estimate [8] of $|V_{\rm ub}/V_{\rm cb}|^2$ leads to a prediction of charmless two-body branching fractions at the level of 10^{-7}, which is near the current sensitivity of present experiments.

The data sample used for this search contains $(87.9 \pm 1.0) \times 10^6$ $\Upsilon(4S) \to B\overline{B}$ decays collected by the *BABAR* detector [9] at the SLAC PEP-II e^+e^- asymmetric-energy storage ring. The primary detector components used in the analysis are a charged-particle tracking system consisting of a five-layer silicon vertex detector and a 40-layer drift chamber surrounded by a 1.5-T solenoidal magnet, and a dedicated particle identification system consisting of a detector of internally reflected Cherenkov light (DIRC).

Two-body B decays are reconstructed from pairs of oppositely-charged tracks originating from the interaction region and having momentum greater than 100 MeV/c in the direction transverse to the beam line. We require each track to have an associated Cherenkov angle (θ_c) measurement with at least four signal photons detected in the DIRC. To suppress combinatorial background arising from Λ decays, we require that the two tracks form a vertex with probability greater than 10^{-3}.

Signal candidates are identified kinematically with two variables: the difference ΔE between the center-of-mass (CM) energy of the B candidate and $\sqrt{s}/2$, where $\sqrt{s}$ is the total CM energy, and the beam-energy substituted mass $m_{\rm ES} = \sqrt{(s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)^2/E_i^2 - \mathbf{p}_B^2}$, with the B-candidate momentum $\mathbf{p_B}$ and the four-momentum of the initial state $(E_i, \mathbf{p_i})$ defined in the laboratory frame. For signal decays, ΔE peaks near zero with a resolution of about 23 MeV, while $m_{\rm ES}$ peaks near the B mass with a resolution of about 2.6 MeV/c^2. We require $5.20 < m_{\rm ES} < 5.29$ GeV/c^2 and $|\Delta E| < 100$ MeV.

Protons are identified based on the θ_c measurement from the DIRC and the momentum measurement from the tracking system. Figure 1 shows the difference between measured and expected values of θ_c for the proton hypothesis, divided by the error σ_{θ_c}, for tracks from $B^0 \to p\bar{p}$ candidates in the sideband region $5.20 < m_{\rm ES} < 5.26$ GeV/c^2. Protons peak near zero and are well separated from the much larger background of pions and kaons. We require a θ_c measurement within $5\sigma_{\theta_c}$ of the expected value for a proton, which removes over 97% of the combinatorial background while retaining more than 91% of the signal decays (the efficiency is less than 100% due to the presence of non-gaussian tails in the pull distribution).

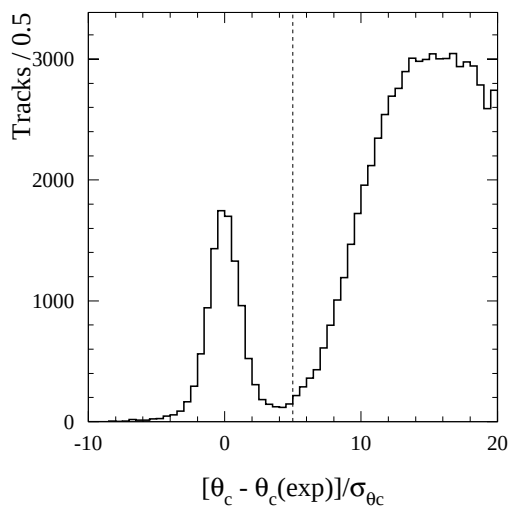

FIG. 1: The difference between the measured and expected values of θ_c, divided by the error, for tracks from $B^0 \to p\bar{p}$ candidates in the region $5.20 < m_{\rm ES} < 5.26$ GeV/c^2. We only use tracks that lie on the left side of the dashed line.

We measure the efficiency of the θ_c selection in a sample of $\Lambda \to p\pi^-$ decays reconstructed in 9.6 fb^{-1} of e^+e^- annihilation data recorded 40 MeV below the $\Upsilon(4S)$ resonance. The sample is selected using kinematic and decay-vertex information, and has a purity of 98.5%. For consistency with $B^0 \to p\bar{p}$ decays, we require the proton CM momentum p^* to be in the range $2.2 < p^* < 2.8$ GeV/c.

Due to the unique topology and kinematics of the two-body final state, $b \to c$ decays do not populate the signal region for $B^0 \to p\bar{p}$, and backgrounds from $b \to u$ decays are negligible after the proton selection. We verify both assertions by analyzing a sample of approximately 80 fb^{-1} of $\Upsilon(4S) \to B\overline{B}$ Monte Carlo simulated events in which the B mesons decay according to the world-average

branching fractions [8], and a second sample corresponding to approximately $200\,\mathrm{fb}^{-1}$ where one B meson in each event is forced to decay to a charmless final state. No event passes the above selection requirements in either sample.

The dominant background is from random combinations of protons produced in the process $e^+e^- \to q\bar{q}$ ($q = u, d, s$). We verify in Monte Carlo samples that the background from the process $e^+e^- \to c\bar{c}$ is negligible compared to light-quark production. In contrast to the spherical topology of $B\overline{B}$ events, particles produced in light-quark events tend to lie near the thrust axis of the original $q\bar{q}$ pair. To suppress this background, we calculate the angle θ_S between the sphericity axis of the B candidate and the sphericity axis of the remaining particles in the event, and require $|\cos\theta_S| < 0.9$. This requirement removes 70% of the combinatorial background, while retaining 85% of the signal decays. In addition, we define a Fisher discriminant $\mathcal{F}$ [10], which is a sum of two discriminating variables with coefficients optimized to separate signal and light-quark events. The first variable is the scalar sum of the CM momenta of all the particles in the event, excluding the two tracks from the $B^0 \to p\bar{p}$ candidate. The second variable is the product $p^* \left(\cos\theta^*\right)^2$ summed over all particles (excluding the B-candidate tracks), where θ^* is the angle between its momentum and the B-candidate thrust axis in the CM frame.

The total efficiency for all of the above selection criteria is $(35.8 \pm 3.7)\%$, where the error includes the statistical and systematic uncertainties added in quadrature. The dominant source of the uncertainty is due to the limited statistical precision of the Λ control sample after applying the proton p^* constraint. A total of 804 events satisfy the $B^0 \to p\bar{p}$ selection criteria.

The signal yield is determined from a maximum likelihood fit that uses m_{ES}, ΔE, and $\mathcal{F}$ as discriminating variables. The likelihood for the sample is defined as

$$\mathcal{L} = e^{-(N_{\mathrm{S}}+N_{\mathrm{B}})} \prod_{i=1}^{N} \left[N_{\mathrm{S}} \mathcal{P}_{\mathrm{S}}^{i} + N_{\mathrm{B}} \mathcal{P}_{\mathrm{B}}^{i} \right], \qquad (1)$$

where N is the total number of events in the sample, N_{S} and N_{B} are the signal (S) and background (B) yields, and $\mathcal{P}_{\mathrm{S}}^{i}$ and $\mathcal{P}_{\mathrm{B}}^{i}$ are the signal and background probability density functions (PDFs) evaluated for event i. The PDFs are calculated from the product of PDFs for the individual variables, which are taken to be uncorrelated in the fit. We verify this assumption by calculating the linear correlation coefficient for each pair of variables. The largest correlation (-13%) is between m_{ES} and ΔE in signal decays, and we have confirmed that the effect of this small correlation is negligible. The signal yield is determined by minimizing the function $-2\ln\mathcal{L}$ with respect to N_{S} and N_{B}.

We use data and Monte Carlo samples to model the PDF shapes for signal decays. The mean and resolution of m_{ES} are dominated by the beam energy, and are therefore similar in decay modes where the momentum resolution of the B candidate is significantly better than the resolution on the beam energy. We obtain the mean and resolution of m_{ES}, and also the mean of ΔE, from a large sample of $B^- \to D^0(K^-\pi^+)\pi^-$ decays reconstructed in data. Due to the difference in momentum resolution between protons and mesons, the resolution on ΔE is different for $p\bar{p}$ and $D^0\pi^-$ decays. We therefore use the value obtained in a large Monte Carlo sample of $B^0 \to p\bar{p}$ decays, and apply a 5% correction to account for the observed difference in ΔE resolution for $D^0\pi^-$ decays reconstructed in data and Monte Carlo samples. For $\mathcal{F}$ we use an asymmetric gaussian function with parameters obtained from simulated events. The shapes of the background PDFs are obtained from data in the sideband regions $100 < |\Delta E| < 200\,\mathrm{MeV}$ and $5.20 < m_{\mathrm{ES}} < 5.26\,\mathrm{GeV}/c^2$. We use a linear shape for ΔE, a double-gaussian function for $\mathcal{F}$, and an empirical threshold function for m_{ES} [11].

Several cross-checks are performed to validate the fitting technique. To confirm that the signal yield is unbiased, we generate and fit a large set of pseudo-experiments where signal and background events are generated randomly from the PDFs. For these studies, we assume a branching fraction of 10^{-6} and find that the fitted signal yield is unbiased. We also check for biases arising from kinematic correlations by mixing Monte Carlo signal events with backgrounds generated directly from the PDFs. No significant biases are observed. The sensitivity of the analysis is determined from a set of pseudo-experiments with assumed branching fractions in the range $(0.1\text{-}1.2)\times10^{-6}$. We find that for any branching fraction above 0.5×10^{-6}, the null hypothesis would be excluded with a probability greater than 99.997%, corresponding to a significance of 5σ for a gaussian distribution.

The result of the fit is $N_{\mathrm{S}} = -0.3^{+3.1}_{-2.0}$, consistent with no signal. We determine a Bayesian 90% confidence-level (C.L.) upper limit on N_{S} by finding the value $N_{\mathrm{S}}^{\mathrm{UL}}$ such that

$$\frac{\int_0^{N_{\mathrm{S}}^{\mathrm{UL}}} \mathcal{L}_{\max} dN_{\mathrm{S}}}{\int_0^{\infty} \mathcal{L}_{\max} dN_{\mathrm{S}}} = 0.90, \qquad (2)$$

where $\mathcal{L}_{\max}$ is the value of the likelihood as a function of N_{S}. We find $N_{\mathrm{S}}^{\mathrm{UL}} = 6.3$ events.

Figures 2(a-c) show projections of the fit result in each of the discriminating variables. The data in the signal region agree well with the background PDF shapes determined from sideband data. As a cross-check on the fit, we apply more stringent background-rejection criteria and determine the signal yield from the observed number of events in a restricted signal region in m_{ES} and ΔE. We require $|\cos\theta_S| < 0.7$, and define the signal region as

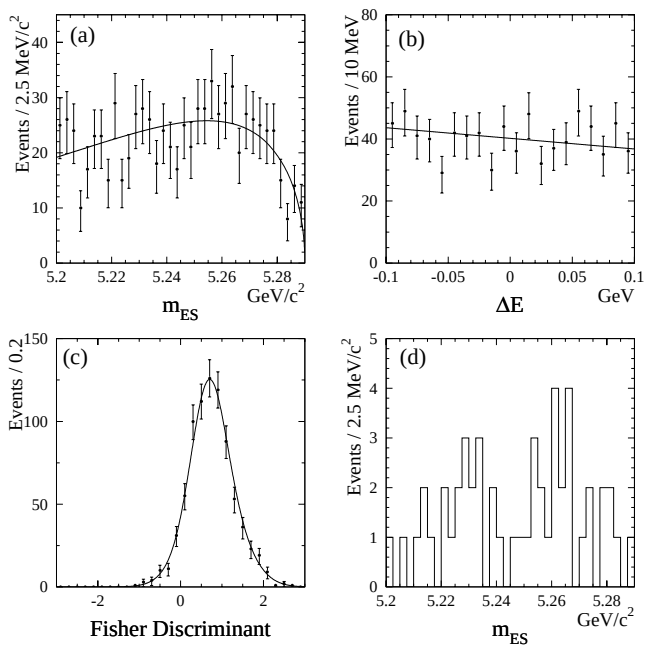

FIG. 2: Data (points with errors) and the result of the maximum likelihood fit (solid line) projected onto the (a) $m_{\rm ES}$, (b) ΔE, and (c) $\mathcal{F}$ variables, and (d) the distribution of $m_{\rm ES}$ for events in the signal-enhanced sample defined by the requirements $|\cos\theta_S| < 0.7$ and $|\Delta E| < 30\,\mathrm{MeV}$.

$|\Delta E| < 30\,\mathrm{MeV}$ and $5.27 < m_{\rm ES} < 5.29\,\mathrm{GeV}/c^2$. Figure 2(d) shows the $m_{\rm ES}$ distribution for events passing the more restrictive $\cos\theta_S$ and ΔE requirements. There are 9 events in the signal region with an expected background of 7.7 ± 1.4, where the background is determined by extrapolating the observed yield in the sideband region $5.2 < m_{\rm ES} < 5.26\,\mathrm{GeV}/c^2$. The signal yield is 1.3 ± 3.3, which is consistent with the null result from the likelihood fit.

Tables I and II summarize the various sources of systematic error on the signal yield and efficiency. Systematic uncertainty on $N_{\rm S}$ may arise from imperfect knowledge of the PDF parameters. We vary each parameter by its estimated error and combine in quadrature the resulting variations in $N_{\rm S}$. For the efficiency of the proton selection, we assign the 1.5% background fraction in the Λ control sample as the correlated systematic error. The efficiency of the vertex quality requirement is determined to be 97.5% from simulated $p\bar{p}$ decays, and we assign a systematic uncertainty of 2.5% to account for possible differences between data and Monte Carlo events. As a cross-check, we compare the efficiency in the topologically similar decays $B^0 \to \pi^+\pi^-$ and $B^0 \to K^+\pi^-$ and find good agreement between data and simulation. Finally, we include a correlated systematic error of 0.8% per track to account for possible differences in tracking efficiency between data and Monte Carlo events. The total systematic uncertainty on the efficiency is computed by adding correlated errors linearly, and then adding the separate sources in quadrature.

TABLE I: Summary of absolute systematic uncertainties on $N_{\rm S}$ from variations in the PDF parameters. The total uncertainty is the sum in quadrature of the individual contributions.

Source	Positive variation	Negative variation
Signal		
$m_{\rm ES}$	$+0.11$	-0.62
ΔE	$+0.39$	-0.37
$\mathcal{F}$	$+0.03$	-0.03
Background		
$m_{\rm ES}$	$+0.32$	-0.30
ΔE	$+0.01$	-0.01
$\mathcal{F}$	$+0.86$	-0.85
Total	$+1.00$	-1.16

TABLE II: Summary of relative statistical and systematic uncertainties on the signal efficiency. The total uncertainty is the sum in quadrature of the individual contributions.

Source	Uncertainty (%)
Statistical	7.7
Tracking	1.6
Vertex Quality	2.5
Proton Selection	3.0
DIRC Acceptance	1.0
$\cos\theta_S$	5.0
Total	10.2

We calculate the 90% C.L. upper limit on the branching fraction by increasing $N_{\rm S}^{\rm UL}$ by the total systematic error on the signal yield, and by decreasing the efficiency and number of $B\overline{B}$ events by their respective total uncertainties. We find the flavor-averaged branching fraction $\mathcal{B}(B^0 \to p\bar{p}) < 2.7 \times 10^{-7}$ at the 90% C.L. This result improves the previous limit [3] by more than a factor of four.

In summary, we have performed a search for the decay $B^0 \to p\bar{p}$ in a sample of 88 million $B\overline{B}$ events. We find no evidence for a signal and set an upper limit on the branching fraction at 2.7×10^{-7}. This result rules out the calculation in [5] based on QCD sum rules, while it is consistent with a recent calculation using the pole model [6], and with simple scaling of the measured branching fraction for the decay $B^0 \to \Lambda_c^- p$.

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§ Deceased

[1] Unless otherwise noted, the charge-conjugate mode is implied throughout this paper, and the term "proton" refers to both protons and antiprotons.
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