Searches for $B^0$ Decays to $\eta K^0$, $\eta\eta$, $\eta\eta'$, $\eta\phi$, and $\eta'\phi$.
University of Cincinnati, Cincinnati, Ohio 45221, USA
University of Colorado, Boulder, Colorado 80309, USA
Colorado State University, Fort Collins, Colorado 80523, USA
Universität Dortmund, Institut für Physik, D-44221 Dortmund, Germany
Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
Harvard University, Cambridge, Massachusetts 02138, USA
University of Iowa, Iowa City, Iowa 52242, USA
Iowa State University, Ames, Iowa 50011-3160, USA
Johns Hopkins University, Baltimore, Maryland 21218, USA
University of Kentucky, Lexington, Kentucky 40506, USA
University of Louisiana at Lafayette, Lafayette, Louisiana 70504, USA
University of Maine, Orono, Maine 04469, USA
University of Massachusetts, Amherst, Massachusetts 01003, USA
University of Michigan, Ann Arbor, Michigan 48109, USA
University of Minnesota, Minneapolis, Minnesota 55455, USA
University of Montana, Missoula, Montana 59812, USA
University of Nebraska, Lincoln, Nebraska 68588, USA
University of Nevada, Las Vegas, Nevada 89154, USA
University of Notre Dame, Notre Dame, Indiana 46556, USA
Ohio State University, Columbus, Ohio 43210, USA
University of Oregon, Eugene, Oregon 97403, USA
University of Padova, Padova, Italy
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
University of Perugia, Perugia, Italy
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
Prairie View A&M University, Prairie View, Texas 77446, USA
Princeton University, Princeton, New Jersey 08544, USA
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
Universität Rostock, D-18051 Rostock, Germany
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
DSM/Dapnia, CEA/Saclay, F-91191 Gif-sur-Yvette, France
University of South Carolina, Columbia, South Carolina 29208, USA
Stanford Linear Accelerator Center, Stanford, California 94309, USA
Stanford University, Stanford, California 94305-4060, USA
State University of New York, Albany, New York 12222, USA
University of Tennessee, Knoxville, Tennessee 37996, USA
University of Texas at Austin, Austin, Texas 78712, USA
University of Texas at Dallas, Richardson, Texas 75083, USA
Università di Torino, Dipartimento di Fisica Sperimentale and INFN, I-10125 Torino, Italy
Università di Trieste, Dipartimento di Fisica and INFN, I-34127 Trieste, Italy
IFIC, Universitat de Valencia-CSIC, E-46071 Valencia, Spain
University of Victoria, Victoria, British Columbia, Canada V8W 3P6
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
University of Wisconsin, Madison, Wisconsin 53706, USA
We report the results of searches for \( B^0 \) or \( \bar{B}^0 \) meson decays to two charmless pseudoscalar mesons, \( \eta K^0, \eta \eta, \eta' \), and to the pseudoscalar-vector combinations \( \eta \phi, \eta' \phi \). None of these decays has been observed previously; the published experimental upper limits on their branching fractions lie in the range \((2 - 10) \times 10^{-6}\). The theoretical predictions for these branching fractions are less than a few per million by most estimates. Theoretical approaches include those based on flavor SU(3) relations, effective Hamiltonians with factorization and specific \( B \)-to-light-meson form factors, perturbative QCD, QCD factorization, and soft collinear effective theory (SCET). Important advances in the theoretical understanding of hadronic charmless two-body B meson decays have occurred in the past few years. With more precise experimental results one can test and constrain the models. Improved measurements of decays with isoscalar mesons can also help to better understand the large difference between the branching fractions for \( B \to \eta' K \) and \( B \to \eta K \) decays.

Branching fractions or limits in the \( \eta \eta, \eta' \eta', \eta \phi, \) and \( \eta' \phi \) channels are relevant for the accuracy with which CP-violating asymmetry measurements can be interpreted. The coefficient \( S \) of the CP-violating sinusoidal factor in the time evolution of \( \eta' K^0 \) and \( \phi K^0 \) can be related to the CKM phase \( \beta = \arg (-V_{cd} V_{cb}^*) \) if these decays are dominated by a single weak phase. Additional higher-order amplitudes with different weak phases would lead to deviations \( \Delta S \) between the value measured in these rare modes and the precise determination in the more copious \( B^0 \) decays to charmonium-\( K^0 \) final states. SU(3) flavor symmetry relates the strength of such additional amplitudes to the decay rates of certain two-body \( B^0 \) decays, including \( \eta \eta, \eta' \eta', \eta \phi, \) and \( \eta' \phi \).

The results presented here are based on data collected with the \( \text{BaBar} \) detector at the PEP-II asymmetric-energy \( e^+ e^- \) collider located at the Stanford Linear Accelerator Center. An integrated luminosity of 289 fb\(^{-1}\), corresponding to \( N_{\text{B\overline{B}}} = 324 \) million \( B \overline{B} \) pairs, was recorded at the \( \Upsilon(4S) \) resonance (center-of-mass energy \( \sqrt{s} = 10.58 \) GeV).

Charged particles produced in \( e^+ e^- \) interactions are detected, and their momenta measured, by a combination of a vertex tracker, consisting of five layers of double-sided silicon microstrip detectors, and a 40-layer central drift chamber, both operating in the 1.5 T magnetic field of a superconducting solenoid. We identify photons and electrons using a CsI(Tl) electromagnetic calorimeter. Further charged-particle identification is provided by the average energy loss (\( dE/dx \)) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region.

We select \( \eta, \eta', \phi, \rho^0, K^0_S, \) and \( \pi^0 \) candidates through the decays \( \eta \to \gamma \gamma (\eta_\gamma \gamma), \eta \to \pi^+ \pi^- \pi^0 (\eta_\pi \pi), \eta' \to \eta \eta^+ \eta^- \) with \( \eta \to \gamma \gamma (\eta_\gamma \gamma), \eta' \to \rho^0 \gamma (\eta_\rho \gamma), \phi \to K^+ K^- \), \( \rho^0 \to \pi^+ \pi^- \), \( K^0_S \to \pi^+ \pi^- \), and \( \pi^0 \to \gamma \gamma \). The photon energy \( E_\gamma \) must be greater than 30 (100) MeV for \( \pi^0 \) (prompt \( \eta \) from \( B \) candidates, greater than 200 MeV in \( \eta' \to \rho \gamma \), and greater than 50 (100) MeV in \( \eta_\pi \pi \) in the \( B \to \eta_\pi \pi \eta_\pi \pi \) decay mode). We make the following requirements on the invariant masses (in MeV/c\(^2\)): \( 490 < m_{\gamma \gamma} < 600 \) for \( \eta_\gamma \gamma \), \( 120 < m_{\gamma \gamma} < 150 \) for \( \pi^0 \), \( 510 < m_{\pi \pi} < 1000 \) for \( \rho^0 \), \( 520 < m_{\pi \pi} < 570 \) for \( \eta_\pi \pi \), \( 930 < m_{\pi \pi} < 990 \) for \( \eta_\pi \pi \eta_\pi \pi \), \( 910 < m_{\pi \pi} < 1000 \) for \( \eta_\rho \gamma \), \( 1005 < m_{K^+ K^-} < 1035 \) for \( \phi \), and \( 480 < m_{\pi \pi} < 510 \) for \( K^0_S \). For \( K^0_S \) candidates we also require a vertex \( \chi^2 \) probability larger than 0.001 and a reconstructed decay length greater than three times its uncertainty. Secondary charged pions in \( \eta \) and \( \eta' \) candidates are rejected, if their DIRC and \( dE/dx \) signatures are consistent with protons, electrons, or kaons. Similarly, tracks from \( \phi \) decays are required to be inconsistent with protons, electrons, and pions.

A \( B \) meson candidate is characterized kinematically by the energy-substituted mass \( m_{\text{ES}} = \sqrt{(E_p + P_0 \cdot P_B)^2 - E_0^2 - P_B^2} \) and energy difference \( \Delta E = E_B - E_T \), where the subscripts 0 and \( B \) refer to the initial \( \Upsilon(4S) \) and to the \( B \) candidate, respectively, and the asterisk denotes the \( \Upsilon(4S) \) rest frame.

Backgrounds arise primarily from random combinations of tracks and neutral clusters in \( e^+ e^- \to q\overline{q} \) continuum events, where \( q = u, d, s, \) or \( c \). We reject these events by using the angle \( \theta_T \) between the thrust axis of the \( B \) candidate in the \( \Upsilon(4S) \) frame and that of the rest of the event. The thrust axis of the \( B \) candidate is obtained as the thrust axis of the \( B \) decay products. The distribution of \( |\cos \theta_T| \) is sharply peaked near 1.0 for combinations drawn from jet-like \( q\overline{q} \) pairs, and is nearly uniform for \( \Upsilon(4S) \to B \overline{B} \) events. We require \( |\cos \theta_T| < 0.9 \). To dis-
criminate against τ-pair and two-photon backgrounds we require the event to contain at least three tracks or one track more than the topology of our final state, whichever is larger. In decays containing a prompt ηγγ, from B we require |H| < 0.9 to remove random combinations with soft photons, where H is defined below. If an event has multiple B candidates, we select the candidate with the highest B vertex χ2 probability or using a χ2 quantity computed with the η or η′ masses, depending on the decay mode. More details on the analysis technique can be found in Ref. [17].

We obtain yields from unbinned extended maximum-likelihood (ML) fits. The principal input observables are ΔE, mES, and a Fisher discriminant F [15]. Where relevant, the invariant masses mres of the intermediate resonances and angular variables H defined below are used. The Fisher discriminant F combines four variables: the angles with respect to the beam axis of the B momentum and B thrust axis (in the Υ(4S) frame), and the zeroth and second angular moments L0,2 of the energy flow about the B′ thrust axis. The moments are defined by Lj = ∫p × [cos θi]j dσ, where θi is the angle with respect to the B thrust axis of track or neutral cluster i, p is its momentum, and the sum excludes the B candidate. For ηγγ (φ), Hj (Hφ) is defined as the cosine of the angle between the direction of a daughter γ (K) and the flight direction of the parent of η (φ) in the η (φ) rest frame; for η′γ, Hρ is the cosine of the angle between the direction of a ρ daughter and the flight direction of the η′ in the ρ rest frame. The set of probability density functions (PDF) used in ML fits, specific to each decay mode, is determined on the basis of studies with Monte Carlo (MC) simulated samples [19]. We estimate B̅B backgrounds using MC samples of B decays. The estimated B̅B background is found to be negligible for all of our decay modes except ηγγK0S and ηγγφ.

The extended likelihood function is

\[ L = \exp \left( -\sum_{j=1}^{3} n_j \right) \prod_{i=1}^{N} \sum_{j=1}^{3} n_j P_j(x_i) \]

where N is the number of input events, n_j is the number of events for hypothesis j (j = 1 for signal, j = 2 for continuum background, and j = 3 for B̅B background), and P_j(x_i) is the corresponding PDF evaluated with the observables x_i of the i-th event. The B̅B background component is used in the decay modes ηγγK0S and ηγγφ. Since the correlations among the observables in the data are small, we take each P_j as the product of the PDFs for the separate variables. We determine the PDF parameters from simulation for the signal and from sideband data (5.25 < mES < 5.27 GeV/c²; 0.1 < |ΔE| < 0.2 GeV) for continuum background. We float some of the continuum PDF parameters in the ML fit. We parameterize each of the functions P_j(mES), P_j(ΔE), P_j(F), and the peaking components of P_j(mres) with either a Gaussian, the sum of two Gaussians, or a Crystal Ball function [20] as required to describe the distribution. Slowly varying distributions (mres and ΔE for combinatorial background, and angular variables) are represented by linear or quadratic functions. The combinatorial background in mES is described by the ARGUS function [21]. Large data control samples of B decays to charmed final states of similar topology are used to verify the simulated resolutions in mES and ΔE. Where the control samples reveal differences between data and MC in mass or energy resolution, we shift or scale the resolution used in the likelihood fits. The bias in the fit is determined from a large set of simulated experiments, each one with the same number of q̅q and signal events as in data.

Table I shows the measured yields, efficiencies, and products of daughter branching fractions for each decay mode. The efficiency is calculated as the ratio of the numbers of signal MC events after the cut based selection to the total generated. We compute the branching fractions from the fitted signal event yields, reconstruction efficiency, daughter branching fractions, and the number of produced B mesons, assuming equal production rates of charged and neutral B pairs at Υ(4S). We correct the yield for any bias measured with the simulations. We combine results from different channels by adding the values of −2 ln L (parameterized in terms of the branching fraction), taking into account the correlated and uncorrelated systematic errors. We report the statistical significance and the branching fractions for the individual decay channels. For the combined measurements we also report the 90% confidence level (CL) upper limits.

The statistical error on the signal yield is taken as the change in the central value when the quantity −2 ln L increases by one unit from its minimum value. The significance is taken as the square root of the difference between the value of −2 ln L (with systematic uncertainties included) for zero signal and the value at its minimum. We determine a Bayesian 90% CL upper limit assuming a uniform prior probability distribution by finding the branching fraction below which lies 90% of the total of the likelihood integral in the positive branching fraction region.

Figure II shows, for representative fits, the projections onto mES and ΔE for the five decay modes. The points show the data after a channel-dependent requirement on the probability ratio P1/(P1 + P2 + P3), optimized to enhance the signal sensitivity and with the probabilities P_j evaluated without using the variable plotted. The solid curves show the total rescaled fit functions.

The main sources of systematic error include uncertainties in the PDF parameterization (0-2 events) and ML fit bias (0-2 events). We evaluate these uncertainties with simulated experiments by varying the PDF parameters within their errors and by embedding MC signal events inside background distributions simulated from PDFs. The uncertainty on N_B̅π is 1.1%. Published world
TABLE I: Fitted signal event yield, fit bias, detection efficiency $\epsilon$, daughter branching fraction product $\prod B_i$, significance $S$, and measured branching fraction $B$ with statistical error for each decay mode. For the combined measurements we give the significance (with systematic uncertainties included) and the branching fraction with statistical and systematic uncertainty (in parentheses the 90% CL upper limit).

| Mode          | Yield (ev) | Fit bias (ev) | $\epsilon$ (%) | $\prod B_i$ (%) | $S$ ($\sigma$) | $B(10^{-6})$ |
|---------------|------------|---------------|-----------------|-----------------|----------------|---------------|
| $\eta_{K^0}$  | $19^{+10}_{-9}$ | $+0.8 \pm 0.6$ | 26.7  $\pm$ 0.9 | 13.5            | 2.6            | $1.5^{+0.9}_{-0.9}$ |
| $\eta_{K^0}$  | $11^{+9}_{-5}$  | $+1.1 \pm 0.4$ | 17.3  $\pm$ 0.6 | 7.8             | 2.7            | $2.4^{+1.4}_{-1.1}$ |
| $\eta K^0$    |            |               |                 |                 | 3.5            | $1.8^{+0.7}_{-0.6} \pm 0.1$ (< 2.9) |
| $\eta_{K^0\gamma}$ | $17^{+10}_{-9}$ | $+3.9 \pm 0.6$ | 20.8  $\pm$ 1.3 | 15.5            | 1.9            | $1.3^{+0.9}_{-0.9}$ |
| $\eta_{K^0\pi\pi}$ | $10^{+7}_{-5}$  | $+0.5 \pm 0.4$ | 18.3  $\pm$ 1.2 | 17.9            | 2.1            | $0.9^{+0.6}_{-0.5}$ |
| $\eta_{K^0\eta\pi}$ | $2^{+2}_{-2}$   | $+0.3 \pm 0.4$ | 11.6  $\pm$ 0.8 | 5.1             | 1.1            | $1.1^{+1.0}_{-1.0}$ |
| $\eta$        |            |               |                 |                 | 3.0            | $1.1^{+0.5}_{-0.4} \pm 0.1$ (< 1.8) |
| $\eta_{\Phi}$ | $-11^{+7}_{-5}$ | $-2.4 \pm 0.6$ | 32.3  $\pm$ 1.2 | 19.4            | 0.0            | $-0.4^{+0.3}_{-0.2}$ |
| $\eta_{\Phi\eta}$ | $6^{+4}_{-2}$   | $+0.8 \pm 0.3$ | 20.7  $\pm$ 1.0 | 11.1            | 1.5            | $0.7^{+0.5}_{-0.5}$ |
| $\eta^*\phi^*$ | $1^{+3}_{-2}$   | $-0.6 \pm 0.3$ | 23.1  $\pm$ 1.1 | 8.6             | 0.8            | $0.3^{+0.3}_{-0.3}$ |
| $\eta^*\phi$  | $-3^{+8}_{-9}$  | $-1.0 \pm 0.4$ | 22.5  $\pm$ 0.9 | 14.5            | 0.0            | $-0.2^{+0.7}_{-0.9}$ |
| $\eta \pi \pi$ | $1^{+1}_{-0}$   | $+0.3 \pm 0.2$ | 15.2  $\pm$ 1.0 | 3.1             | 1.2            | $0.8^{+0.7}_{-0.7}$ |
| $\eta \pi \pi$ | $9^{+1}_{-0}$   | $+1.5 \pm 0.3$ | 17.6  $\pm$ 0.8 | 10.3            | 1.5            | $1.2^{+1.0}_{-0.9}$ |
| $\eta \eta$   |            |               |                 |                 | 1.8            | $1.0^{+0.8}_{-0.6} \pm 0.1$ (< 2.4) |

FIG. 1: Signal enhanced projections on $m_{ES}$ (left) and $\Delta E$ (right) in the decays: (a, b) $\eta K^0$, (c, d) $\eta \eta$, (e, f) $\eta \phi$, (g, h) $\eta^* \phi$, (i, j) $\eta^* \eta^*$. Points with error bars (statistical only) represent the data (combined measurements), the solid line the full fit function, and the dashed line its background component.

In summary, we present updated measurements of branching fractions for five $B^0$ decays to charmless meson pairs. Our results represent substantial improvements on the previous upper limits [2, 3].

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averages provide the uncertainties in the $B$-daughter branching fractions (1-7%). Other sources of systematic uncertainty are track (1-3%) and neutral cluster (2-6%) reconstruction efficiencies. The validity of the fit procedure and PDF parameterization, including the effects of unmodeled correlations among observables, is checked with simulated experiments.

Grossman et al. [14] introduced a method to determine a bound on $|\Delta S_f| = |S_f - \sin 2\beta|$ where $f$ is a $CP$ eigenstate produced in charmless $B^0$ decays and $S$ is the coefficient of the $CP$-violating sinusoidal factor mentioned above. The method relies on SU(3) flavor symmetry and the measured branching fractions of charmless, strangeness-conserving $B^0$ decays to constrain the unknown contributions of suppressed amplitudes in $B^0 \to f$. Two of the channels in our study, $\eta \eta$ and $\eta^* \eta^*$, are relevant to the $\Delta S_f$ bound for $f = \eta' K^0$, while two others, $\eta \phi$ and $\eta^* \phi$, are relevant for $f = \phi K^0$. Using the technique described in Ref. [22] and evaluating 90% CL upper limits, we find $|\Delta S_{\eta' K^0}| < 0.15$ and $|\Delta S_{\phi K^0}| < 0.38$. This new $\Delta S_{\eta' K^0}$ bound also makes use of our recent results [22] on the $B^0 \to \eta' \eta$, $\eta' \pi^0$, and $\eta \pi^0$ channels.
Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

† Also with Università della Basilicata, Potenza, Italy

[1] The charge conjugate of the named state is implicitly included, here and throughout this paper.

[2] BTeV Collaboration, B. Aubert et al., Phys. Rev. Lett. 93, 181806 (2004).

[3] BTeV Collaboration, B. Aubert et al., Phys. Rev. Lett. 95, 131803 (2005).

[4] H. K. Fu et al., Phys. Rev. D 69, 074002 (2004); H. K. Fu et al., Nucl. Phys. Proc. Suppl. 115, 279 (2003).

[5] C. W. Chiang et al., Phys. Rev. D 68, 074012 (2003); C. W. Chiang et al., Phys. Rev. D 70, 034020 (2004).

[6] C. W. Chiang et al., Phys. Rev. D 69, 034001 (2004).

[7] M. Bauer et al., Z. Phys. C 34, 103 (1987); A. Ali and C. Greub, Phys. Rev. D 57, 2996 (1998); A. Ali, G. Kramer, and C. D. Lu, Phys. Rev. D 58, 094009 (1998); Y. H. Chen et al., Phys. Rev. D 60, 094014 (1999); J.-H. Jang et al., Phys. Rev. D 59, 034025 (1999).

[8] G. P. Lepage and S. Brodsky, Phys. Rev. D 22, 2157 (1980); J. Botts and G. Sterman, Nucl. Phys. B 325, 62 (1989); Y. Y. Keum et al., Phys. Lett. B 504, 6 (2001), Phys. Rev. D 63, 054006 (2001); Y. Y. Keum and H. N. Li, Phys. Rev. D 63, 074008 (2001); Z. Xiao et al., arXiv:hep-ph/0607219 v1, 2006 [and references therein].

[9] M. Beneke et al., Phys. Rev. Lett. 83, 1914 (1999), Nucl. Phys. B 606, 245 (2001); M. Beneke and M. Neubert, Nucl. Phys. B 651, 225 (2003), Nucl. Phys. B 675, 333 (2003).

[10] C. W. Bauer et al., Phys. Rev. D 63, 014006 (2001); C. W. Bauer et al., Phys. Rev. D 63, 114020 (2001); C. W. Bauer and I. W. Stewart, Phys. Lett. B 516, 134 (2001); C. W. Bauer, arXiv:hep-ph/0606018 v1, 2006.

[11] A. R. Williamson and J. Zupan, Phys. Rev. D 74, 014003 (2006) [and references therein].

[12] H. J. Lipkin, Phys. Lett. B 633, 540 (2006).

[13] Particle Data Group, S. Eidelman et al., Phys. Lett. B 592, 1 (2004).

[14] Y. Grossman et al., Phys. Rev. D 68, 015004 (2003).

[15] M. Gronau et al., Phys. Lett. B 596, 107 (2004).

[16] BTeV Collaboration, B. Aubert et al., Nucl. Instr. Methods Phys. Res., Sect. A 479, 1 (2002).

[17] BTeV Collaboration, B. Aubert et al., Phys. Rev. D 70, 032006 (2004).

[18] R. A. Fisher, Annals of Eugenics 7, 179 (1936).

[19] The BTeV detector Monte Carlo simulation is based on GEANT4: S. Agostinelli et al., Nucl. Instr. Methods Phys. Res., Sect. A 506, 250 (2003).

[20] Crystal Ball Collaboration, T. Skwarnicki, “A Study of the Radiative Cascade Transitions Between the $\Upsilon'$ and $\Upsilon$ Resonances,” DESY-F31-86-02, 1986.

[21] ARGUS Collaboration, H. Albrecht et al., Phys. Lett. B 241, 278 (1990).

[22] Babar Collaboration, B. Aubert et al., arXiv:hep-ex/0606050 v1, 2006.

[23] Babar Collaboration, B. Aubert et al., Phys. Rev. D 73, 071102 (2006).