Title
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Permalink
https://escholarship.org/uc/item/8998931k

Journal
Physical Review D - Particles, Fields, Gravitation and Cosmology, 75(5)

ISSN
1550-7998

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Publication Date
2007-03-14

DOI
10.1103/PhysRevD.75.051102

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Peer reviewed
Measurement of $B$ decays to $\phi K\gamma$

MEASUREMENT OF B DECAYS TO $\phi K\gamma$


Rapid Communications

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We search for the decays $B^- \rightarrow \phi K^0 \gamma$ and $B^0 \rightarrow \phi K^0 \gamma$ in a data sample of $228 \times 10^6$ $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the BABAR detector. We measure the branching fraction $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$ and set an upper limit $\mathcal{B}(B^0 \rightarrow \phi K^0 \gamma) < 2.7 \times 10^{-6}$ at the 90% confidence level. We also measure the direct CP asymmetry in $B^- \rightarrow \phi K^- \gamma$, $A_{CP} = (-26 \pm 14 \pm 5)\%$. The uncertainties are statistical and systematic, respectively.

DOI: 10.1103/PhysRevD.75.051102

PACS numbers: 13.25.Hw

Measurements of the branching fractions and CP asymmetries of $b \rightarrow s \gamma$ decays provide a sensitive probe of the standard model (SM), in which these decays are forbidden at tree level but allowed through electroweak penguin processes. They are sensitive to the possible effects of physics beyond the SM manifesting as new virtual particles contributing to loops. These additional contributions to the decay amplitudes could affect branching fractions and CP violation [1]. The SM theoretical prediction [2] and experimental measurements [3] of the $b \rightarrow s \gamma$ inclusive branching fraction have uncertainties of about 10% and are consistent with each other. Although exclusive $b \rightarrow s \gamma$ branching fractions are experimentally easier to determine than inclusive ones, calculations for the exclusive modes are theoretically challenging due to large nonperturbative quantum chromodynamic effects. The expected direct CP asymmetry between $B^+$ and $B^-$ decay rates in the SM is $-(0.1-1)\%$ [4], while the time-dependent CP asymmetry in neutral CP eigenstates such as $B^0 \rightarrow \phi K^0_S \gamma$ should be a few percent [5]. A significantly larger CP asymmetry of either type would be a sign of new physics.

There have already been results published for branching fraction and/or CP asymmetry measurements in several exclusive modes: $B \rightarrow K^\pm \gamma$ [6], $B^0 \rightarrow K^0_S \pi^0 \gamma$ [7], $B \rightarrow \eta(\prime) K \gamma$ [8], and various $B \rightarrow K \pi \pi \gamma$ [9] modes. The Belle Collaboration has measured $\mathcal{B}(B^- \rightarrow \phi K^- \gamma) = (3.4 \pm 0.9 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(B^0 \rightarrow \phi K^0 \gamma) < 8.3 \times 10^{-6}$ at the 90% confidence level using $96 \times 10^6 B\bar{B}$ pairs [10]. We present the first BABAR measurement of the branching fraction for the charged mode $B^- \rightarrow \phi K^- \gamma$ and a search for the neutral mode $B^0 \rightarrow \phi K^0 \gamma$ [11] using $228 \times 10^6$ $B\bar{B}$ pairs. We also measure for the first time the direct CP asymmetry in the charged mode $A_{CP} = [N(B^-) - N(B^+)]/[N(B^-) + N(B^+)]$, where the flavor of the $B$ is determined by the charge of the kaon.

The data used in this analysis were recorded with the BABAR detector at the PEP-II asymmetric storage rings, in which 9.0 GeV electrons collide with 3.1 GeV positrons to produce $\Upsilon(4S)$ mesons. The BABAR detector is described in detail elsewhere [12]. Most important to this analysis is the tracking system composed of the silicon vertex tracker and drift chamber inside a 1.5 T magnetic field, the ring-imaging detector of internally reflected Cherenkov light (DIRC), and the electromagnetic calorimeter (EMC). The tracking system can reconstruct a $B$ decay vertex with a resolution of 70 $\mu m$ along the direction of the beam and has a transverse momentum resolution of 0.52% at 500 MeV/c. The DIRC provides kaon-pion separation of at least 4$\sigma$ significance for momenta up to 3 GeV/c. The EMC detects photons over an energy range from 20 MeV to 500 MeV.

We identify signal $B$ decays through the distributions of two quantities, missing mass and reconstructed mass, that peak around the nominal $B$ mass. The missing mass is $m_{\text{miss}} = \sqrt{|p_Y(4S) - p_B|^2}$, where $p_Y(4S)$ is the $Y(4S)$ four-
momentum and $p_B$ is the four-momentum of the $B \rightarrow \phi K \gamma$ candidate after a mass constraint on the $B$ is applied. The reconstructed mass $m_{rec}$ is the $B$ candidate invariant mass calculated from the reconstructed energy and momentum. We require $5.12 < m_{miss} < 5.32$ GeV/c$^2$ and $4.98 < m_{rec} < 5.48$ GeV/c$^2$. We use this set of variables instead of $m_{ES}$ and $\Delta E$, which are more commonly used in BABAR, because the mass constraint in $m_{miss}$ gives better resolution. More information can be found in Ref. [17]. To further discriminate $B$ decays from continuum $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s, c$) background we use two topological quantities: the ratio of Legendre moments $L_2/L_0$ and the cosine of the angle between the $B$ candidate and the $e^-$ direction in the CM frame $|\cos\theta_B^i|$. We require $L_2/L_0 < 0.55$, where $L_i = \sum |p_i|^i |\cos\theta_B^i|^{i-1}$, $p_i$ is the CM momentum of each particle $j$ not used in the $B$ candidate, and $\theta_B^i$ is the CM angle between the particle’s momentum and the thrust axis of the $B$ candidate. We also require $|\cos\theta_B^i| < 0.9$.

The selection criteria described above are chosen to optimize $N_S/\sqrt{N_S + N_B}$ in the signal region, where $N_S$ and $N_B$ are the MC simulated signal and background yields, respectively, and the signal region is defined by $5.05 < m_{rec} < 5.4$ GeV/c$^2$, $5.27 < m_{miss} < 5.29$ GeV/c$^2$, $|\cos\theta_B^i| < 0.8$, and $L_2/L_0 < 0.48$. Signal MC is based on inclusive $B \rightarrow X_i \gamma$ events generated according to the model of Kagan and Neubert [18], using $m_b = 4.62$ GeV/c$^2$ for the effective $b$ quark mass. Only the part of the hadronic mass spectrum above the $\phi K$ threshold of 1.52 GeV/c$^2$ is used, with $X_i$ forced to decay to $\phi K$. This model does not take resonances into account.

After all criteria are applied, the average candidate multiplicity in events with at least one candidate are 1.01 and 1.07 in the neutral and charged modes, respectively. If multiple $B$ candidates are found in an event, we select the best one based on a $x^2$ from the value and uncertainty of the mass of the $\phi$ candidate and, in the neutral mode, the $K_{S0}$ candidate. Based on signal MC we find the probability of multiple candidates due to alternate charged kaons or photons to be less than 0.1% and therefore negligible. The remaining background comes from continuum combinatorics, nonresonant $B \rightarrow K^{*+}K^{-}\gamma$, $B \rightarrow \phi K\pi^0$, $B \rightarrow \phi K\eta$, and a small contribution from $b \rightarrow c$ decays.

Signal and background yields are extracted from a fit to an unbinned extended maximum likelihood function defined by

$$L(N_S, N_B, \alpha) = e^{-(N_S+N_B)} \prod_i^N (N_S P_S(\tilde{x}_i) + N_B P_B(\tilde{x}_i; \alpha));$$

(1)

$N_S$ and $N_B$ are the number of signal and background events, respectively, the index $i$ labels each event in the data set, and $N$ is the total number of events used in the fit. $P_S$ and $P_B$ are products of the one-dimensional signal and background probability density functions (PDFs) for each of the observables $\alpha = \{m_{miss}, m_{rec}, L_2/L_0, \cos\theta_B^i\}$. The signal shape parameters are fixed in the fit while the background parameters $\alpha$ are allowed to vary. In order to fit the $CP$ asymmetries of signal and background in the charged mode, the number of $B^+$ and $B^-$ events is determined separately: $N_{j}^o = \textstyle{1 \over 2}(1 \mp \mathcal{A}_P^{j})n_j$, where $j = S$ or $B, n_j$ and $\mathcal{A}_P^{j}$ are the total yield and $CP$ asymmetry of species $j$, respectively, and the upper (lower) signs correspond to the positively (negatively) charged $B$ mesons.

The signal PDFs for $m_{miss}$ and $m_{rec}$ are parametrized by

$$f(x) = \exp\left[{-x^2 \over 2\sigma_{LR}^2 + \alpha_{LR}x^2}\right].$$

(2)

where the parameters $\sigma_{LR}$ and $\alpha_{LR}$ determine the core width and variation of the width on either side of $x = 0$, $x$ being the difference from the nominal $B$ mass of $m_{miss}$ or $m_{rec}$. The $m_{miss}$ background PDF is an ARGUS function [19], with the end point calculated event-by-event as $\sqrt{s} - m_p$, where $\sqrt{s}$ is the center of mass energy. The $m_{rec}$ background PDF is modeled as a 2nd degree polynomial. The signal and background models for $L_2/L_0$ both use a binned PDF with eight bins. The $\cos\theta_B^i$ distribution is modeled as a 2nd degree polynomial in both signal and background; true $B$ candidates follow a $1 - \cos^2\theta_B^i$ distribution if the detector efficiency is flat in $\cos\theta_B^i$.

To determine the signal PDF parameters we use a high-statistics $B^0 \rightarrow K^{*0}(\rightarrow K^\pm \pi^\mp)\gamma$ sample. Once determined, these parameters are fixed for the fit to $B \rightarrow \phi K\gamma$ data. We determine the selection efficiency by performing a fit of the yields on signal MC, with the shape being that of the MC.

We apply several corrections to the signal yield and efficiency before determining the branching fractions. Studies of simulated events show that the main sources of signal-like (peaking) backgrounds are nonresonant $B \rightarrow K^{*+}K^-\gamma$ events, and $B \rightarrow \phi K\pi^0$ or $B \rightarrow \phi K\eta$, where one of the photons from the $\pi^0$ or $\eta$ decay is lost and the other is picked up as the signal high-energy photon. We estimate the amount of $B \rightarrow K^{*+}K^-\gamma$ contamination by fitting for the yield in $\phi$ mass sideband regions defined by $989 < m_\phi < 1009$ MeV/c$^2$ and $1029 < m_\phi < 1049$ MeV/c$^2$. By interpolating into the signal region, we find and correct for $0.0 \pm 1.5$ and $5 \pm 4$ events for the neutral and charged modes, respectively. These contributions are subtracted from the event yields determined in the fit. From the known branching fraction [3] of $B \rightarrow \phi K^*(\rightarrow K\pi^0)$ we correct for a contamination of $0.27 \pm 0.16$ neutral and $1.98 \pm 0.32$ charged events, based on an ensemble of simulated experiments using embedded MC events of this type. There have been no branching fraction measurements of $B \rightarrow \phi K^0$ or $B \rightarrow \phi K\eta$. We assume that the branching fraction of the first is no more than one-third that of $B \rightarrow \phi K^+$ and that of the latter is no more than $B \rightarrow \phi K^+$. Based on this we assign an uncertainty of 0.5
neutral and 2.9 charged events due to nonresonant $B \to \phi K^0(\pi^0/\eta)$ background. The small $b \to c$ background is absorbed into the floating shape of the continuum background. To correct for our limited knowledge of the form of the background PDF, we generate 1000 simulated experiments using PDFs with separate components for $B\bar{B}$ and continuum, and embedding signal events from the full simulation. The background components are generated using shape parameters determined from the full MC simulation. We correct for a bias of $+4.1 \pm 0.5$ events in the charged mode, due to correlations among the observables in signal MC events that are not accounted for in the fit. In the neutral mode we find a bias of $-0.06 \pm 0.20$, so we apply no correction but include 0.20 events in the systematic uncertainty of the yield. We find no bias in the number of background events in a fit to the full MC simulation.

We correct for efficiency differences between data and MC in charged track, single photon, and $K_S^0$ reconstruction. Charged-track efficiency differences are obtained from a large sample of $\pi$ pairs with 1 versus 3 topology. Single photon corrections are based on $\pi^0$ samples. $K_S^0$ corrections are based on a large, pure $K^0_S$ sample and are a function of transverse momentum, transverse flight distance, and azimuthal angle. The above multiplicative efficiency corrections are 0.956 in the neutral mode and 0.975 in the charged mode. The corrected efficiencies are $(15.3 \pm 0.8)$% in the neutral mode and $(21.9 \pm 1.6)$% in the charged mode, where the uncertainties are systematic (discussed below).

The signal yields, efficiencies, branching fractions, and charged mode CP asymmetry are reported in Table I. We calculate the central value of the branching fractions by

$$B_i = \frac{N_i}{N_B \cdot e_i \cdot b_i},$$

where $i$ labels either the neutral or charged mode, $N_S^i$ is the corrected signal yield, $N_B$ is the number of $B\bar{B}$ pairs recorded, $e_i$ is the corrected efficiency, and $b_i$ is $B_i(\phi \to K^+ K^-) \frac{1}{2} B_i(K_S^0 \to \pi^+ \pi^-)$ in the neutral mode and $B_i(\phi \to K^+ K^-)$ in the charged mode. The world average branching fractions are taken from Ref. [16]. We measure $B(B \to \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$ and $B(B^0 \to \phi K^0 \gamma) = (1.3 \pm 1.0 \pm 0.3) \times 10^{-6}$. In the charged mode we measure $A_{CP} = (-26 \pm 14 \pm 5)$%. In Fig. 1 we show fits to the data projected onto $m_{\text{miss}}$ and $m_{\text{rec}}$. In all cases, the displayed distribution is created with the signal region selection applied to all other fit variables. We determine the consistency of the branching fraction measurements with the assumption of isospin symmetry using 1000 simulated experiments in each mode with the number of signal events determined by the average branching fraction, $B_{av} = 2.8 \times 10^{-6}$. From the distribution of the differences in branching fraction between the modes we find an 8.9% probability to measure a difference greater than or equal to that observed in data.

For the neutral mode we compute the 90% confidence level upper limit on the branching fraction. We use a Bayesian approach with a flat prior probability for the branching fraction in the physical region $0 \leq B \leq 1$ and zero elsewhere. As the likelihood [Eq. (1)] is a function of several parameters, we determine its dependence on $N_S$ by fixing $N_S$ to a series of values and recomputing the likelihood at each one, allowing $N_B$ and $\tilde{a}$ to be reoptimized to

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Yield</th>
<th>Efficiency (%)</th>
<th>$B(10^{-6})$</th>
<th>$A_{CP}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^- \to \phi K^- \gamma$</td>
<td>85 $\pm$ 15 $\pm$ 7</td>
<td>21.9 $\pm$ 1.6(syst)</td>
<td>3.5 $\pm$ 0.6 $\pm$ 0.4</td>
<td>$-26 \pm 14 \pm 5$</td>
</tr>
<tr>
<td>$\bar{B}^0 \to \phi \bar{K}^0 \gamma$</td>
<td>8 $\pm$ 6 $\pm$ 2</td>
<td>15.3 $\pm$ 0.8(syst)</td>
<td>1.3 $\pm$ 1.0 $\pm$ 0.3</td>
<td>$&lt;2.7$</td>
</tr>
</tbody>
</table>

| TABLE I. Summary of the branching fractions and direct CP asymmetry. In $B^0 \to \phi K^0 \gamma$ the 90% confidence level upper limit is also given. |

FIG. 1 (color online). Missing mass (a) and reconstructed mass (b) fits in the signal region for the charged mode and the neutral mode (c,d). The dotted curves show the background contribution while the solid curves show the sum of signal and background.
obtain the maximum likelihood at each point. We convolve this function with a Gaussian distribution of width equal to the systematic uncertainty of the yield. Similarly, for the efficiency uncertainty we also use a Gaussian distribution of width equal to the efficiency systematic uncertainty. We determine the branching fraction upper bound $B_{UB}$ from the following expression:

$$
\int_0^{B_{UB}} \mathcal{L}(B)dB / \int_0^1 \mathcal{L}(B)dB = 90\%. \tag{4}
$$

After applying the previously discussed corrections to the yield and efficiency, and including systematic uncertainties, we obtain $B(B^0 \rightarrow \phi K^0\gamma) < 2.7 \times 10^{-6}$.

We assign a systematic uncertainty to the yield due to the fixed signal parameters in the fit. We vary these parameters within the ranges allowed by the $K^+\gamma$ sample to determine the total uncertainty of the yields. We account for other systematic uncertainties due to the previously mentioned efficiency differences between data and MC in charged kaon tracking, kaon PID, photon selection, and $K^0_S$ selection efficiency. Uncertainties in $\phi$ selection efficiency are determined by fitting the $\phi$ mass peak in data and MC. There are small uncertainties assigned to the $L_2/L_0$ selection and the $\pi^0/\eta$ veto, also due to data-MC efficiency differences.

Figure 2 shows the efficiency-corrected $\phi K$ invariant mass distributions, using the background subtraction technique described in Ref. [20]. In the charged mode, we find that no more than 50% of the spectrum in the 1.6–3.0 GeV/$c^2$ range can come from the $K_S^0(1770)$ resonance, and we use this information to bound the uncertainty due to the assumed MC $\phi K$ mass spectrum. We determine what the efficiency would have been if half of the mass spectrum came from resonant $K_S^0(1770) \rightarrow \phi K$ production, while the other half came from the signal MC model. We assign the relative efficiency difference between this and the nominal model as an uncertainty. Adding all of the previously discussed uncertainties in quadrature, we find a total multiplicative uncertainty of 5.2% in the neutral mode and 7.1% in the charged mode. The complete systematic uncertainties for each mode are summarized in Table II.

For the direct $CP$ asymmetry measurement we bound the $K^+ / K^-$ efficiency asymmetry of the detector by using the measured combinatoric background asymmetry, which is consistent with zero within an uncertainty of 1.8%. To account for uncertainty due to various peaking background sources we assume that each source can have a $CP$ asymmetry of up to $\pm 58\%$, which is the root mean square width of a flat distribution between $-1$ and $1$. We multiply this by the expected fractional contamination in the data sample to

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \phi K^0\gamma$</td>
<td>$K K^+ K^- \gamma$ Subtraction</td>
</tr>
<tr>
<td>$B^- \rightarrow \phi K^-\gamma$</td>
<td>Peaking background</td>
</tr>
<tr>
<td></td>
<td>Fit bias</td>
</tr>
<tr>
<td></td>
<td>Fit PDF parameters</td>
</tr>
<tr>
<td></td>
<td>Yield uncertainty</td>
</tr>
<tr>
<td>Taon tracking</td>
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</tr>
<tr>
<td>$K^0_S$ efficiency</td>
<td>1.5</td>
</tr>
<tr>
<td>$\phi$ efficiency</td>
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</tr>
<tr>
<td>Particle ID</td>
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</tr>
<tr>
<td>Single photon efficiency</td>
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</tr>
<tr>
<td>Photon spectrum model</td>
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<tr>
<td>$L_2/L_0$ cut</td>
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</tr>
<tr>
<td>$\pi^0/\eta$ veto</td>
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</tr>
<tr>
<td>Efficiency uncertainty</td>
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</tr>
<tr>
<td>$BB$ counting</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td>$^{+23}_{-22}$</td>
</tr>
</tbody>
</table>
obtain the systematic uncertainty. For \( B^- \rightarrow \phi K^- (\pi^0/\eta) \) we assign 1.8% uncertainty, while for \( B^- \rightarrow K^- K^+ K^- \gamma \) we assign 3.5% uncertainty. For resonant \( B \rightarrow \phi K^0 (\rightarrow K^0 \eta) \) events, the previous BABAR and Belle measurements [21] show that the CP asymmetry is consistent with zero to within 15%. We therefore consider it to be negligible. As was done with the branching fraction measurement, we vary the fixed signal parameters of the fit to obtain a 2.2% uncertainty for the signal CP asymmetry. Adding the uncertainties in quadrature we find a total \( \Delta A_{CP} \) systematic uncertainty of 5%.

In summary, we have performed the first BABAR studies of \( B \rightarrow \phi K \gamma \) decay modes. We measure \( B(B^- \rightarrow \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6} \), consistent with the result from Belle. We have set a limit \( B(B^0 \rightarrow \phi K^0 \gamma) < 2.7 \times 10^{-6} \) at the 90% confidence level. Lastly, we have made the first measurement of the direct CP asymmetry in \( B^- \rightarrow \phi K^- \gamma \): \( \Delta A_{CP} = (-26 \pm 14 \pm 5)\% \).

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 U.S. 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, Ministerio de Educación y Ciencia (Spain), and the Particle Physics and Astronomy Research Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

[11] Throughout this paper, whenever a mode is given, the charge conjugate is also implied.