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

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

-Measurements of the branching fractions and *CP* asymmetries of $b \to s\gamma$ 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 $b \to s\gamma$ inclusive branching fraction have uncertainties of about 10% and are consistent with each other. Although exclusive $b \to s\gamma$ 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 $B^0 \to \phi K_S^0 \gamma$ 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: $B \to K^* \gamma$ [6], $B^0 \to K_S^0 \pi^0 \gamma$ [7], $B \to \eta^{(\prime)} K \gamma$ [8], and various $B \to K\pi\pi\gamma$ [9] modes. The Belle Collaboration has measured $\mathcal{B}(B^- \to \phi K^- \gamma) = (3.4 \pm 0.9 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \to \phi \bar{K}^0 \gamma) < 8.3 \times 10^{-6}$ at the 90% confidence level using 96×10^6 $B\bar{B}$ pairs [10]. We present the first *BABAR* measurement of the branching fraction for the charged mode $B^- \to \phi K^- \gamma$ and a search for the neutral mode $\bar{B}^0 \to \phi \bar{K}^0 \gamma$ [11] using 228×10^6 $B\bar{B}$ pairs. We also measure for the first time the direct *CP* asymmetry in the charged mode $\mathcal{A}_{CP} = [N(B^-) - N(B^+)]/[N(B^-) + N(B^+)]$, 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 $Y(4S)$ mesons. The *BABAR* detector is described in detail elsewhere [12]. Most important to this analysis are 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 μm 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 4σ significance for momenta up to 3 GeV/c. The EMC detects photons over an energy range from 20 MeV to 9 GeV, with a resolution of 2.6% at 2.5 GeV. A detailed Monte Carlo (MC) simulation of signal and background processes was performed using the EVTGEN generator [13] and the GEANT4 package [14].

We search for $B \to \phi K \gamma$ candidates based on charged track combinations and the presence of a high-energy photon using a kinematic fitter [15] to reconstruct the intermediate mesons and the *B*. Each decay vertex is required to have a χ^2 probability greater than 0.1%. Candidates for $\phi \to K^+ K^-$ are selected from pairs of oppositely charged tracks that have been distinguished from pions based on a particle identification (PID) likelihood selection algorithm that uses dE/dx and Cherenkov light measurements. The same PID algorithm is used for the single K^- from the B^- in the charged mode. We keep ϕ candidates with masses within a ± 10 MeV/c^2 ($\simeq 4.6\sigma$) window of the nominal ϕ mass [16]. In the neutral mode, pairs of oppositely charged tracks are accepted as K_S^0 candidates if they have a combined invariant mass within ± 10 MeV/c^2 ($\simeq 2.9\sigma$) of the K_S^0 mass and if the K_S^0 flight length is greater than 3 times its uncertainty. We require the combined ϕK invariant mass to be less than 3.0 GeV/c^2. In the neutral mode a D^0 veto is applied by removing candidates with combined ϕK invariant mass within ± 10 MeV/c^2 of the D^0 mass. Photon candidates are reconstructed from EMC clusters that are not associated with charged tracks, are isolated from other clusters, and have the expected photon lateral shower shape. We require an energy of 1.5–2.6 GeV in the $e^+ e^-$ center of mass (CM) frame and we veto photon candidates that form a $\pi^0(\eta)$ candidate with invariant mass between 115–155 MeV/c^2 (470–620 MeV/c^2) when combined with another photon of energy greater than 50 MeV (250 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 $m_{\rm rec}$ is the B candidate invariant mass calculated from the reconstructed energy and momentum. We require $5.12 < m_{\rm miss} < 5.32$ GeV/c^2 and $4.98 < m_{\rm rec} < 5.48$ GeV/c^2. We use this set of variables instead of $m_{\rm ES}$ and ΔE, which are more commonly used in *BABAR*, because the mass constraint in $m_{\rm miss}$ 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 $|\cos\theta_B^*|$. We require $L_2/L_0 < 0.55$, where $L_i = \sum_j |p_j^*| |\cos\theta_j^*|^i$, p_j^* is the CM momentum of each particle j not used in the B candidate, and θ_j^* is the CM angle between the particle's momentum and the thrust axis of the B candidate. We also require $|\cos\theta_B^*| < 0.9$.

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 $5.05 < m_{\rm rec} < 5.4$ GeV/c^2, $5.27 < m_{\rm miss} < 5.29$ GeV/c^2, $|\cos\theta_B^*| < 0.8$, and $L_2/L_0 < 0.48$. Signal MC is based on inclusive $B \rightarrow X_s \gamma$ 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 ϕK threshold of 1.52 GeV/c^2 is used, with X_s forced to decay to ϕK. 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 χ^2 formed from the value and uncertainty of the mass of the ϕ candidate and, in the neutral mode, the K_S^0 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 $B \rightarrow KK^+K^-\gamma$, $B \rightarrow \phi K \pi^0$, $B \rightarrow \phi K \eta$, 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

$$\mathcal{L}(N_S, N_B, \vec{\alpha}) = e^{-(N_S + N_B)} \prod_i^N [N_S \mathcal{P}_S(\vec{x}_i)$$
$$+ N_B \mathcal{P}_B(\vec{x}_i; \vec{\alpha})]; \qquad (1)$$

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. $\mathcal{P}_S$ and $\mathcal{P}_B$ are products of the one-dimensional signal and background probability density functions (PDFs) for each

of the observables $\vec{x} = \{m_{\rm miss}, m_{\rm rec}, L_2/L_0, \cos\theta_B^*\}$. The signal shape parameters are fixed in the fit while the background parameters $\vec{\alpha}$ 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: $N_j^{\pm} = \frac{1}{2}(1 \mp \mathcal{A}_{CP}^j) n_j$, where $j = S$ or B, n_j and $\mathcal{A}_{CP}^j$ 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 $m_{\rm miss}$ and $m_{\rm rec}$ are parametrized by

$$f(x) = \exp\left[\frac{-x^2}{2\sigma_{L,R}^2 + \alpha_{L,R}x^2}\right], \qquad (2)$$

where the parameters $\sigma_{L,R}$ and $\alpha_{L,R}$ 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 $m_{\rm miss}$ or $m_{\rm rec}$. The $m_{\rm miss}$ background PDF is an ARGUS function [19], with the end point calculated event-by-event as $\sqrt{s} - m_B$, where $\sqrt{s}$ is the center of mass energy. The $m_{\rm rec}$ 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 $\cos\theta_B^*$ distribution is modeled as a 2nd degree polynomial in both signal and background; true B candidates follow a $1 - \cos^2\theta_B^*$ distribution if the detector efficiency is flat in $\cos\theta_B^*$.

To determine the signal PDF parameters we use a high-statistics $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\gamma$ 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 $B \rightarrow KK^+K^-\gamma$ events, and $B \rightarrow \phi K \pi^0$ or $B \rightarrow \phi K \eta$, where one of the photons from the π^0 or η decay is lost and the other is picked up as the signal high-energy photon. We estimate the amount of $B \rightarrow KK^+K^-\gamma$ contamination by fitting for the yield in ϕ 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 ± 1.5 and 5 ± 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 ± 0.16 neutral and 1.98 ± 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 $B \rightarrow \phi K \pi^0$ 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

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

Decay mode	Yield	Efficiency (%)	$\mathcal{B}(10^{-6})$	$\mathcal{A}_{CP}$ (%)
$B^- \to \phi K^- \gamma$	$85 \pm 15 \pm 7$	$21.9 \pm 1.6(\text{syst})$	$3.5 \pm 0.6 \pm 0.4$	$-26 \pm 14 \pm 5$
$\bar{B}^0 \to \phi \bar{K}^0 \gamma$	$8 \pm 6 \pm 2$	$15.3 \pm 0.8(\text{syst})$	$1.3 \pm 1.0 \pm 0.3$	
	<16		<2.7	

neutral and 2.9 charged events due to nonresonant $B \to \phi K(\pi^0/\eta)$ 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 ± 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 τ pairs with 1 versus 3 topology. Single photon corrections are based on π^0 samples. K_S^0 corrections are based on a large, pure K_S^0 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

$$\mathcal{B}_i = \frac{N_S^i}{N_{B\bar{B}} \cdot \varepsilon_i \cdot b_i}, \qquad (3)$$

where *i* labels either the neutral or charged mode, N_S^i is the corrected signal yield, $N_{B\bar{B}} = (228.3 \pm 2.5) \times 10^6$ is the number of $B\bar{B}$ pairs recorded, ε_i is the corrected efficiency, and b_i is $\mathcal{B}(\phi \to K^+K^-)[\frac{1}{2}\mathcal{B}(K_S^0 \to \pi^+\pi^-)]$ in the neutral mode and $\mathcal{B}(\phi \to K^+K^-)$ in the charged mode. The world average branching fractions are taken from Ref. [16]. We measure $\mathcal{B}(B^- \to \phi K^- \gamma) = (3.5 \pm 0.6 \pm 0.4) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \to \phi \bar{K}^0 \gamma) = (1.3 \pm 1.0 \pm 0.3) \times 10^{-6}$. In the charged mode we measure $\mathcal{A}_{CP} = (-26 \pm 14 \pm 5)\%$. In Fig. 1 we show fits to the data projected onto m_{miss} and m_{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, $\mathcal{B}_{\text{av}} = 2.8 \times 10^{-6}$. 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 $0 \le \mathcal{B} \le 1$ 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 $\vec{\alpha}$ to be reoptimized to
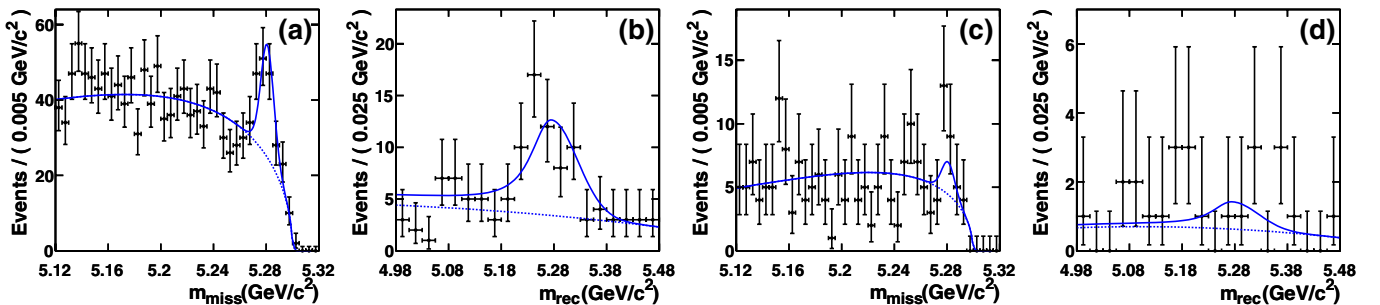

FIG. 1 (color online). Missing mass (a) and reconstructed mass (b) fits in the signal region for the charged mode and the neutral mode (c,d). The dotted curves show the background contribution while the solid curves show the sum of signal and background.
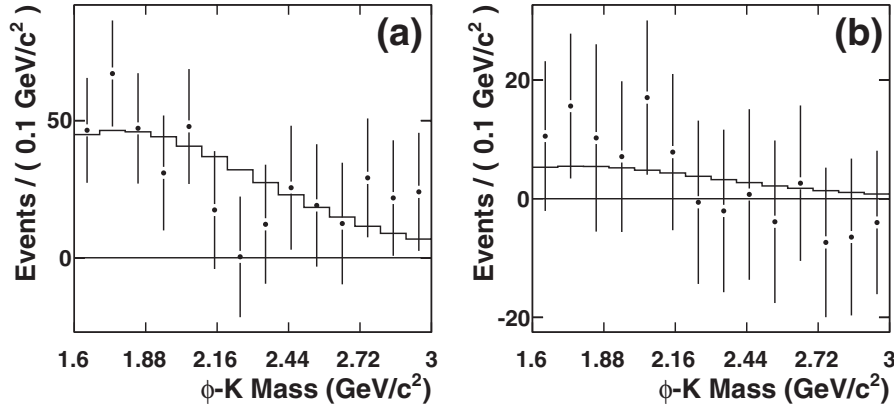
FIG. 2.   The background-subtracted and efficiency-corrected ϕK mass distributions (points with uncertainties) for the charged mode (a) and the neutral mode (b). The signal MC model for the mass spectrum, based on Ref. [18], is shown as a histogram without uncertainties and is normalized to the efficiency-corrected signal yield obtained in data.

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 $\mathcal{B}_{\mathrm{UB}}$ from the following expression:

$$\int_0^{\mathcal{B}_{\mathrm{UB}}} \mathcal{L}(\mathcal{B})d\mathcal{B} \Big/ \int_0^1 \mathcal{L}(\mathcal{B})d\mathcal{B} = 90\%. \qquad (4)$$

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

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_S^0 selection efficiency. Uncertainties in ϕ selection efficiency are determined by fitting the ϕ mass peak in data and MC. There are small uncertainties assigned to the L_2/L_0 selection and the π^0/η veto, also due to data-MC efficiency differences.

Figure 2 shows the efficiency-corrected ϕK 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 $K_2(1770)$ resonance, and we use this information to bound the uncertainty due to the assumed MC ϕK mass spectrum. We determine what the efficiency would have been if half of the mass spectrum came from resonant $K_2(1770) \to \phi K$ 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 II.   Summary of the systematic uncertainties. Except where noted, all uncertainties are given as percentages.

Source	Uncertainty (%)	
	$\bar{B}^0 \to \phi\bar{K}^0\gamma$	$B^- \to \phi K^-\gamma$
$KK^+K^-\gamma$ Subtraction	19.7	5.2
Peaking background	6.4	3.4
Fit bias	2.6	0.6
Fit PDF parameters	$+7.0 \atop -5.9$	$+5.9 \atop -5.2$
Yield uncertainty	$+1.8 \atop -1.7$ events	$+7.3 \atop -6.9$ events
Kaon tracking	2.8	4.2
K_S^0 efficiency	1.5	0
ϕ efficiency	1.7	1.7
Particle ID	2.8	4.2
Single photon efficiency	1.8	1.8
Photon spectrum model	0.4	2.6
L_2/L_0 cut	1.2	1.2
π^0/η veto	1.0	1.0
Efficiency uncertainty	**5.2**	**7.1**
$B\bar{B}$ counting	**1.1**	**1.1**
Total	$+23 \atop -22$	± 11

obtain the systematic uncertainty. For $B^- \to \phi K^- (\pi^0/\eta)$ we assign 1.8% uncertainty, while for $B^- \to K^- K^+ K^- \gamma$ we assign 3.5% uncertainty. For resonant $B \to \phi K^* (\to K\pi^0)$ 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 $\mathcal{A}_{CP}$ systematic uncertainty of 5%.

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

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