First Observation of Radiative $B^0 \rightarrow φK^0\gamma$ Decays and Measurements of Their Time-Dependent $CP$ Violation

H. Sahoo,7 T. E. Browder,7 I. Adachi,8 D. M. Asner,36 V. Aulchenko,1,34 A. M. Bakich,43 E. Barberio,25 K. Belous,13 V. Bhardwaj,37 B. Bhuyan,9 A. Bondar,1,34 A. Bozek,30 M. Bracko,23,15 O. Brovchenko,17 A. Chen,26 P. Chen,29 B. G. Cheon,8 K. Cho,18 Y. Choi,42 J. Dalenso,24,45 Z. Doležal,2 Z. Drášal,2 S. Eidelman,1,34 D. Epifanov,1,34 J. E. Fast,36 V. Gaur,44 N. Gabyshev,1,34 J. Haba,8 K. Hayasaka,26 H. Hayashii,27 Y. Horii,47 Y. Hoshi,46 W.-S. Hou,29 Y. B. Hsiung,29 H. J. Hyun,20 T. Iijima,26 K. Inami,26 A. Ishikawa,47 R. Itoh,8 M. Iwabuchi,54 Y. Iwasaki,8 T. Iwashita,27 N. J. Joshi,44 T. Julius,25 J. H. Kang,54 T. Kawasaki,32 C. Kiesling,24 H. J. Kim,20 H. O. Kim,20 J. B. Kim,19 J. H. Kim,18 K. T. Kim,19 M. J. Kim,20 S. K. Kim,41 Y. J. Kim,18 K. Kinoshita,8 B. R. Ko,19 N. Kobayashi,38,49 S. Koblmüller,24 P. Kodyš,2 S. Korpar,23,15 P. Križan,22,15 T. Kuhr,17 R. Kumar,37 T. Kumita,50 A. Kuzmin,1,34 Y.-J. Kwon,54 J. S. Lange,4 M. J. Lee,41 S.-H. Lee,19 J. Li,41 Y. Li,52 J. Libby,10 C.-L. Lim,54 Z. Q. Liu,11 D. Liventsev,14 R. Louvot,21 D. Matvienko,1,34 S. McOnie,43 K. Miyabayashi,27 H. Miyata,32 Y. Miyazaki,26 R. Mizuk,14 G. B. Mohanty,44 T. Mori,26 M. Nakao,8 Z. Natkansieczynski,30 C. Ng,48 S. Nishida,8 K. Nishimura,7 O. Nitoh,51 T. Nozaki,5 T. Ohshima,26 S. Okuno,16 S. L. Olsen,41,7 Y. Onuki,47 P. Pakhlov,14 G. Pakhlova,14 C. W. Park,42 H. K. Park,20 T. Peng,40 R. Pestotnik,15 M. Petric,15 L. E. Piilonen,52 M. Prim,17 M. Röhrken,17 S. Ryu,41 K. Sakai,8 Y. Sakai,8 T. Sanuki,47 O. Schneider,21 C. Schwanda,12 A. J. Schwartz,3 K. Senyo,26 O. Seon,26 M. E. Sevior,25 M. Shapkin,13 V. Shebalin,1,34 T.-A. Shibata,38,49 J.-G. Shiu,29 B. Shwartz,1,34 F. Simon,24,45 P. Smerkol,15 Y.-S. Sohn,54 A. Sokolov,13 E. Solovieva,14 S. Stanic,33 M. Staric,15 M. Sumihama,38,5 K. Sumisawa,8 T. Suniysawa,50 S. Suzuki,39 G. Tashchivli,30 Y. Teramoto,35 K. Trabelsi,8 M. Uchida,38,49 T. Uguro,14 Y. Unno,8 S. Uno,8 Y. Ushiroda,8 S. E. Vahsen,7 G. Varner,7 A. Vinokurova,1,34 M. Watanabe,32 Y. Watanabe,16 K. M. Williams,52 E. Won,19 B. D. Yabsley,43 Y. Yamashita,31 C. Z. Yuan,13 Y. Yusa,52 C. C. Zhang,11 Z. P. Zhang,40 V. Zhilich,1,34 P. Zhou,53 V. Zhulanov,1,34 and A. Zupanc17

(The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Faculty of Mathematics and Physics, Charles University, Prague
3University of Cincinnati, Cincinnati, Ohio 45221
4Justus-Liebig-Universität Gießen, Gießen
5Gifu University, Gifu
6Hanyang University, Seoul
7University of Hawaii, Honolulu, Hawaii 96822
8High Energy Accelerator Research Organization (KEK), Tsukuba
9Indian Institute of Technology Guwahati, Guwahati
10Indian Institute of Technology Madras, Madras
11Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
12Institute of High Energy Physics, Vienna
13Institute of High Energy Physics, Protvino
14Institute for Theoretical and Experimental Physics, Moscow
15J. Stefan Institute, Ljubljana
16Kanagawa University, Yokohama
17Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie, Karlsruhe
18Korea Institute of Science and Technology Information, Daejeon
19Korea University, Seoul
20Kyungpook National University, Taegu
21École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
22Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
23University of Maribor, Maribor
24Max-Planck-Institut für Physik, München
25University of Melbourne, School of Physics, Victoria 3010
26Nagoya University, Nagoya
27Nara National University, Nara
28National Central University, Chung-li
29Department of Physics, National Taiwan University, Taipei
30H. Niewodniczanski Institute of Nuclear Physics, Krakow
31Nippon Dental University, Niigata
32Niigata University, Niigata
33University of Nova Gorica, Nova Gorica
34Novosibirsk State University, Novosibirsk
We report the first observation of the radiative decay $B^0 \to \phi K^0 \gamma$ using a data sample of $772 \times 10^6 B \bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We observe a signal of $37 \pm 8$ events with a significance of 5.4 standard deviations including systematic uncertainties. The measured branching fraction is $B(B^0 \to \phi K^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively. We also report the first measurements of time-dependent $CP$ violation parameters: $S_{\phi K^0 \gamma} = +0.74^{+0.72}_{-1.07}$ (stat) $^{+0.19}_{-0.23}$ (syst) and $A_{\phi K^0 \gamma} = +0.35 \pm 0.58$ (stat) $^{+0.10}_{-0.08}$ (syst). Furthermore, we measure $B(B^+ \to \phi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$, $A_{CP} = -0.03 \pm 0.11 \pm 0.08$ and find that the signal is concentrated in the $M_{\phi K}$ mass region near threshold.

PACS numbers: 14.40.Nd, 13.25.Hw, 11.30.Er

Rare radiative $B$ meson decays play an important role in the search for physics beyond the standard model (SM). These are flavor changing neutral current decays, forbidden at tree level in the SM but allowed through electroweak loop processes. The loop can be mediated by non-SM particles (for example, charged Higgs or SUSY particles) and therefore is sensitive to new physics (NP). Here we report the first observation of a new $b \to s$ radiative penguin decay mode, $B^0 \to \phi K^0 \gamma$, as well as measurements of its time-dependent $CP$ asymmetry. This type of decay is sensitive to NP from right-handed currents [1] and will be useful for precise time-dependent measurements at future high-luminosity flavor facilities [2,3,4].

The emitted photons in $b \to s \gamma \ (\bar{b} \to \bar{s} \gamma)$ decays are predominantly left-handed (right-handed) in the SM, and hence the time-dependent $CP$ asymmetry is suppressed by the quark mass ratio ($2m_s/m_b$). The expected mixing-induced $CP$ asymmetry parameter ($S$) is $O(3\%)$ and the direct $CP$ asymmetry parameter ($A$) is $\sim 0.6\%$ [1]. In several extensions of the SM, both photon helicities can contribute to the decay. Therefore, any significantly larger $CP$ asymmetry would be clear evidence for NP. In contrast to $B^0 \to K^{*0} (\to K^0 \pi^0) \gamma$ [3,4,5], another related mode that is sensitive to NP, the time dependence of $B^0 \to \phi K^0 \gamma$ can be measured from the $\phi \to K^+ K^-$ decay and does not require a difficult measurement of the long lived $K^0$ decay inside the inner tracking volume or reconstruction of a low energy $\pi^0$. The $B \to \phi K^0 \gamma$ mode can be used to search for a possible contribution from kaonic resonances decaying to $\phi K$. Furthermore, we can also probe the photon polarization using the angular distributions of the final state hadrons [7].

Results on $B \to \phi K \gamma$ decays have been reported by both Belle and BaBar collaborations based on $96 \times 10^6 B \bar{B}$ [8] and $228 \times 10^6 B \bar{B}$ [9] pairs, respectively. Only upper limits on $B(B^0 \to \phi K^0 \gamma)$ were given. Here we report the first observation of $B^0 \to \phi K^0 \gamma$, the first measurements of time-dependent $CP$ violation in this mode, as well as more precise measurements of $B^+ \to \phi K^+ \gamma$ [10]. The data set used consists of $772 \times 10^6 B \bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector [11] at the KEKB asymmetric-energy $e^+e^-$ (3.5 on 8.0 GeV) collider [12].

At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta \gamma = 0.425$ along the $z$ axis, which is defined as opposite to the $e^+$ beam direction. In the decay chain $\Upsilon(4S) \to B^0 \bar{B}^0 \to f_{\text{rec}} f_{\text{tag}}$, where one of the $B$ mesons decays at time $t_{\text{rec}}$ to the signal mode $f_{\text{rec}}$ and the other decays at time $t_{\text{tag}}$ to a final state $f_{\text{tag}}$ that distinguishes between $B^0$ and $\bar{B}^0$, the decay rate has a time depen-
fake rate. A less restrictive selection has an efficiency of 90% for kaons and an 8% pion likelihood ratio \( \Delta t \) and \( \Delta \) depend on a charged (neutral) mode have more than one for further analysis. Using Monte Carlo (MC) simulation when the tagging is approximately at rest in the \( \Upsilon(4S) \) center-of-mass system (c.m.s.), \( \Delta t \) can be determined from \( \Delta z \); the displacement in \( z \) between the two decay vertices: \( \Delta t \simeq \Delta z/(\beta c) \).

Signal candidates are reconstructed in the \( B^+ \to \phi K^+\gamma \) and \( B^0 \to \phi K_S^0 \gamma \) modes, with \( \phi \to K^+K^- \) and \( K_S^0 \to \pi^+\pi^- \). Charged kaons are identified by requiring a likelihood ratio \( L_{K/\pi} = [L_K/(L_K + L_\pi)] > 0.6 \), which is calculated using information from the aerogel Cherenkov, time-of-flight, and drift chamber detectors. This requirement has an efficiency of 90% for kaons and an 8% pion fake rate. A less restrictive selection \( L_{K/\pi} > 0.4 \) is applied to the kaon candidates that are used to reconstruct the \( \phi \) meson. The invariant mass of the \( \phi \) candidates is required to satisfy \( |M_{K^+K^-} - m_\phi| < 10 \text{ MeV/c}^2 \), where \( m_\phi \) denotes the \( \phi \) meson world-average mass [13]. The \( K_S^0 \) selection criteria are the same as those described in Ref. [14]; the invariant mass of the pion pairs should be in the range \( M_{\pi^+\pi^-} \in [482, 514] \text{ MeV/c}^2 \). The high energy prompt photons must lie in the barrel region of the calorimeter (ECL), have a c.m.s. energy \( E^{\gamma}_{\text{c.m.s.}} \in [1.4, 3.4] \) GeV and a shower shape consistent with that of a photon. We also suppress the background photons from \( \pi^0(\eta) \to \gamma\gamma \) using a likelihood \( L_{\pi^0}(L_{\eta}) < 0.25 \), as described in Ref. [15].

We combine a \( \phi \) meson candidate, a charged or neutral kaon candidate, and a radiative photon to form a \( B \) meson. \( B \) candidates are identified using two kinematic variables: the energy difference \( \Delta E \equiv E_B^{\gamma} - E_{\text{beam}}^{\gamma} \) and the beam-energy-constrained mass \( M_{bc} \equiv \sqrt{(E_{\text{beam}}^{\gamma}/c^2)^2 - (p_{B}^{\gamma}/c)^2} \), where \( E_{\text{beam}}^{\gamma} \) is the beam energy in the c.m.s. and \( E_B^{\gamma} \) and \( p_B^{\gamma} \) are the c.m.s. energy and momentum, respectively, of the reconstructed \( B \) candidate. In the \( M_{bc} \) calculation, the photon momentum is replaced by \( (E_{\text{beam}}^{\gamma} - E_{\phi K}^{\gamma}) \) to improve its resolution. The candidates that satisfy the requirements \( M_{bc} > 5.2 \text{ GeV/c}^2 \) and \( \Delta E < 0.3 \text{ GeV} \) are retained for further analysis. Using Monte Carlo (MC) simulations, we find nearly 12\% (3\%) of signal events in the charged (neutral) mode have more than one \( B \) candidate. In case of multiple candidates, we choose the best candidate based on a series of selection criteria, which depend on a \( \chi^2 \) variable formed using the candidate’s \( \phi \) mass (and the \( K_S^0 \) mass in the neutral mode) as well as the highest \( E_\gamma^{\gamma} \) and the highest \( L_{K/\pi} \) in the charged mode. For events with multiple candidates, this selection method chooses the correct \( B \) candidate for the charged (neutral) mode 57\% (69\%) of the time.

The dominant background comes from \( e^+e^- \to q\bar{q} \ (q = u, d, s, c) \) continuum events. We use two event-shape variables (a Fisher discriminant formed from modified Fox-Wolfram moments [16] and the cosine of the angle between the \( B \) flight direction and the beam axis, \( \cos \theta_B \), in the c.m.s frame) to distinguish spherically symmetric \( B\bar{B} \) events from the jet-like continuum background. From these variables we form a likelihood ratio, denoted by \( R_s/b \). We require \( R_s/b > 0.65 \), which removes 91\% of the continuum while retaining 76\% of the signal. In addition to the continuum, various \( B\bar{B} \) background sources are also studied. In the \( B^0 \to \phi K_S^0 \gamma \) mode, backgrounds from some \( b \to c \) decays such as \( D^0\pi^0, D^0\eta \) and \( D^-\rho^+ \), peak in the \( M_{bc} \) distribution. We remove the dominant peaking backgrounds by applying a veto to \( \phi K_S^0 \) combinations consistent within detector resolution (\( \pm 4\sigma \)) with the nominal \( D \) mass [13]. Some of the charmless backgrounds, where the \( B \) meson decays to \( \phi K^*(892), \phi K^0 \) and \( \phi \eta \) also peak in \( M_{bc} \) but shift towards lower \( \Delta E \). Another significant background is non-resonant (NR) \( B \to K^+K^-K^- \), which peaks in the \( \Delta E-M_{bc} \) signal region; it is estimated using the \( \phi \) mass sideband, \( M_{K^+K^-} \in [1.05, 1.30] \text{ GeV/c}^2 \), in data.

![Diagram](image.png)

**FIG. 1:** \( \Delta E \) and \( M_{bc} \) projections for \( B^+ \to \phi K^+\gamma \) (upper) and \( B^0 \to \phi K_S^0 \gamma \) (lower). The \( \Delta E \) projections include the requirement \( M_{bc} \in [5.27, 5.29] \text{ GeV/c}^2 \) while the \( M_{bc} \) projections require \( \Delta E \in [-0.08, 0.05] \text{ GeV} \). The points with error bars are the data. The curves show the total fit function (solid red), total background function (long-dashed black), continuum component (dotted blue), the \( b \to c \) component (dashed-dotted green) and the non-resonant component as well as other charmless backgrounds (filled magenta histogram).

The signal yield is obtained from an extended unbinned maximum-likelihood (UML) fit to the two-dimensional \( \Delta E-M_{bc} \) distribution. We model the shape for the signal component using the product of a Crystal Ball line
shape $\pm 1$ for $\Delta E$ and a Gaussian for $M_{bc}$. The continuum background is represented by the product of a first-order polynomial for $\Delta E$ and an ARGUS function for $M_{bc}$. The $b \to c$ background is described by the product of a second-order polynomial for $\Delta E$ and the sum of an ARGUS and a Gaussian function for $M_{bc}$. For the small charmless backgrounds (except for the NR component), we use the sum of two Gaussians for $\Delta E$ and a Gaussian for $M_{bc}$. The probability density function (PDF) is the product of these two functional forms \[19\]. In the final fit the continuum parameters are allowed to vary while all other background parameters are fixed to the values from MC simulations. The shapes of the $b \to c$ and NR peaking background components are fixed to that of the signal. In the charged mode, the NR background yield, $(12.5 \pm 6.7\%)$ of the signal, is fixed from the $\phi$ mass sideband. Since the neutral mode is limited by statistics, we assume isospin symmetry and use the $\phi$ the product of a second-order polynomial for $\Delta E$ and $M$ a sum of an ARGUS and a Gaussian function for $M$. The efficiencies are reweighted according to this ground yield, $(12\%$ to that of the signal. In the charged mode, the NR background yield in each bin is obtained by the fitting procedure described in the text. A three-body phase-space model from MC simulation is shown by the filled circles (blue points) and normalized to the total data signal yield.

To measure the $M_{\phi K}$ distribution, we repeat the fit in bins of $\phi K$ mass and the resulting signal yields are corrected for the detection efficiency. Nearly 72% of the signal events are concentrated in the low-mass region, $M_{\phi K} \in [1.5, 2.0]\ GeV/c^2$, as shown in Fig. \[2\]. The MC efficiencies are reweighted according to this $M_{\phi K}$ dependence. These spectra are consistent with the expectations from the pQCD model for non-resonant $B \to \phi K \gamma$ decays \[20\]. With the present statistics no clear evidence is found for the existence of a kaonic resonance decaying to $\phi K$.

From the signal yield ($N_{\text{sig}}$), we calculate the branching fraction [B] as $N_{\text{sig}}/(\epsilon \times N_{B \bar{B}} \times B_{\text{sec}})$, where $\epsilon$ is the weighted efficiency \[15.3 \pm 0.1\text{(stat)}\%$ for the charged mode and $10.0\pm0.1\text{(stat)}\%$ for the neutral mode], $N_{B \bar{B}}$ is the number of $B \bar{B}$ pairs in the data sample, and $B_{\text{sec}}$ is the product of daughter branching fractions \[13\]. We obtain $B(B^+ \to \phi K^{+}\gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$ and $B(B^0 \to \phi K^{0}\gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively.

We evaluate the systematic uncertainties on the signal yield by fitting the data with each fixed parameter varied by its $\pm 1\sigma$ error, and then taking the quadratic sum of all differences from the nominal value. The largest contribution of 8.0% arises from the NR yield. The other sources of systematic error are from charged track efficiency ($\sim 1.1\%$ per track), photon detection efficiency (2.4%), particle identification (1.4%), number of produced $B \bar{B}$ pairs (1.4%), $\phi$ and $K_S^0$ branching fractions (1.2%), $K_S^0$ reconstruction (4.6%), and the requirement on $R_{s/b}$ (0.3%). The statistical uncertainty on the MC efficiency after reweighting is 1.0% (1.2%) in the charged (neutral) mode. Furthermore, we assign a systematic error of 0.2% (2.7%) for possible fit bias, which is obtained from ensemble tests with MC pseudo-experiments. The total systematic uncertainty on the branching fraction is 9.5% (11.7%).

For the CP asymmetry fit, we select events in the signal region defined as $M_{bc} \in [5.27, 5.29]\ GeV/c^2$ and $\Delta E \in [-0.2, 0.1]\ GeV$. Different selection criteria on $R_{s/b}$ are used depending upon the flavor-tagging information. In addition, ECL endcap region photons are included in the analysis. We use a flavor tagging algorithm \[21\] to obtain the $b$-flavor charge $q$ and a tagging quality factor $r \in [0, 1]$. The value $r = 0$ signifies no flavor discrimination while $r = 1$ implies unambiguous flavor assignment. The data are divided into seven $r$ intervals. The vertex position for the $f_{\text{rec}}$ decay is reconstructed using the two kaon tracks from the $\phi$ meson and that of the $f_{\text{tag}}$ decay is from well-reconstructed tracks that are not assigned to $f_{\text{rec}}$ \[22\]. The typical vertex reconstruction efficiency (z resolution) is 96% (115 $\mu$m) for $f_{\text{rec}}$ and 94% (104 $\mu$m) for $f_{\text{tag}}$. After all selection criteria are applied, we obtain 75 (436) events in the signal region for the CP fit with a purity of 45% (37%) in the neutral (charged) mode.

We determine $S$ and $A$ by performing an UML fit to the observed $\Delta t$ distribution by maximizing the likelihood function $L(S, A; \Delta t_i) = \prod_i P_i(S, A; \Delta t_i)$, where the product is over all events in the signal region. The like-
likelihood $P_i$ for each event is given by

$$P_i = (1 - f_{\text{ol}}) \int \left[ \sum_j f_j P_j(\Delta t') R_j(\Delta t_i - \Delta t') \right] d(\Delta t')$$

$$+ f_{\text{ol}} P_{\text{ol}}(\Delta t_i),$$

(2)

where $j$ runs over signal and all background components. $P_j(\Delta t)$ is the corresponding PDF and $R_j(\Delta t)$ is the $\Delta t$ resolution function. The fraction of each component ($f_j$) depends on the $r$ region and is calculated for each event as a function of $\Delta E$ and $M_{bc}$. The signal PDF is given by a modified form of Eq. (1) by fixing $\tau_{B^0}$ and $\Delta m_{d}$ to their world-average values [13] and incorporating the effect of incorrect flavor assignment. The distribution is then convolved with a resolution function to take into account the finite vertex resolution. Since the NR component is expected to have the same NP as the signal $B \rightarrow \phi K \gamma$, we treat this as signal for the time-dependent fit [22]. For the other $B \bar{B}$ components, we use the same functional forms as signal with an effective lifetime taken from MC and $CP$ parameters fixed to zero. For the continuum background, we use the functional form described in Ref. [22]; the parameters are determined from a fit to the $\Delta t$ distribution of events in the data sideband $M_{bc} < 5.26$ GeV/$c^2$ and $\Delta E \in [0.1, 0.3]$ GeV. The term $P_{\text{ol}}(\Delta t)$ is a broad Gaussian function that represents an outlier component with a small fraction $f_{\text{ol}}$. The PDFs and resolution functions are described in detail elsewhere [22].

We perform various consistency checks of the $CP$ fitting technique. A lifetime fit to the $B^0 \rightarrow K^{\ast 0} \rightarrow K^+ \pi^- \gamma$, $B^+ \rightarrow \phi K^+ \gamma$ and $B^0 \rightarrow \phi K_S^0 \gamma$ data sample yields $1.56 \pm 0.03$ ps, $1.70 \pm 0.20$ ps and $2.09 \pm 0.45$ ps, respectively. These are all consistent with the world-average values of the $B$ lifetimes. The results of the $CP$ asymmetry fit to the $B^0 \rightarrow K^{\ast 0} \rightarrow K^+ \pi^- \gamma$ ($S = +0.02 \pm 0.06$, $A = -0.06 \pm 0.04$) and $B^+ \rightarrow \phi K^+ \gamma$ ($S = +0.25 \pm 0.33$, $A = +0.18 \pm 0.26$) are consistent with zero. A fit to the sideband events in the $B^0 \rightarrow \phi K_S^0 \gamma$ data sample gives an asymmetry consistent with zero ($S = -1.77 \pm 1.30$, $A = -0.04 \pm 0.14$).

The only free parameters in the $CP$ fit are $S$ and $A$.

The results of the fit are $S = +0.74^{+0.72}_{-1.05}(\text{stat})^{+0.10}_{-0.21}($syst$)$ and $A = +0.35 \pm 0.58(\text{stat})^{+0.23}_{-0.10}($syst$)$, where the uncertainties are obtained as described below. We define the raw asymmetry in each $\Delta t$ bin by $(N_+ - N_-)/(N_+ + N_-)$, where $N_+$ ($N_-$) is the number of events with $q = +1$ ($-1$). Figure 3 shows the $\Delta t$ distributions and raw asymmetry for events with good tagging quality ($r > 0.5$, 48% of the total).

We find that the error on $S$ in the MINUIT minimization [24] is much smaller than the expectation from MC simulations and has a probability of only 0.6% [22]. This is due to low statistics and the presence of a single special event (with $\Delta t = -3.64$ ps and $r = 0.96$). A similar effect was found in our early time-dependent analyses of $B^0 \rightarrow \pi^+ \pi^-$ [26]. Instead of the errors from MINUIT, we use the ±68% confidence intervals in the residual distributions of $S$ and $A$, determined from toy MC simulations as the statistical uncertainties on the result.

We evaluate the systematic uncertainties from the following sources. A significant contribution is from the vertex reconstruction ($0.08$ on $S$, $0.04$ on $A$). We refit the data with each fixed parameter varied by its error to evaluate the uncertainties due to signal and background fractions ($0.03$, $0.07$), resolution function ($0.02$, $0.03$), $\Delta E$-$M_{bc}$ shapes ($0.01$, $0.01$), continuum $\Delta t$ PDF ($0.01$, $0.02$), flavor tagging ($0.01$, $0.01$) and effects of tagside interference ($0.04$, $0.03$). The uncertainty from physics parameters ($\tau_{B^0}$, $\Delta m_{d}$), effective lifetime and $CP$ asymmetry of the $B \bar{B}$ background, is ($0.05$, $0.03$). We also include a possible fit bias due to low statistics and the proximity of the central value to the physical boundary ($+0.09$, $+0.21$). MC simulations show that this bias decreases to 0.04 with twice the signal yield. Adding all these contributions in quadrature, we obtain a systematic error of $-0.24$ on $S$ and $-0.16$ on $A$.

In summary, we report the first observation of a new radiative decay mode, $B^0 \rightarrow \phi K_S^0 \gamma$ using a data sample of $772 \times 10^6 B \bar{B}$ pairs. The observed signal yield is $37 \pm 8$ with a significance of 5.4 $\sigma$ including systematic uncertainties, and the measured branching fraction is $B(B^0 \rightarrow \phi K_S^0 \gamma) = (2.74 \pm 0.60 \pm 0.32) \times 10^{-6}$. We also measure $B(B^+ \rightarrow \phi K^+ \gamma) = (2.48 \pm 0.30 \pm 0.24) \times 10^{-6}$ with a significance of 9.6 $\sigma$. Furthermore, we measure the charge asymmetry $A_{CP} = [N(B^-) - N(B^+)]/[N(B^-) + N(B^+)] = -0.03 \pm 0.11 \pm 0.08$, where $N(B^-)$ and $N(B^+)$ are the signal yields for $B^-$ and $B^+$ decays, respectively. The signal events are mostly concentrated at low $\phi K$ mass near threshold. The branching fractions and $\phi K$ mass spectra are in agreement with the theoretical prediction of Ref. [20]. We also report the first measurements of time-dependent $CP$ violation parameters in the neutral mode: $S = +0.74^{+0.72}_{-1.05}(\text{stat})^{+0.10}_{-0.21}($syst$)$ and $A = +0.35 \pm 0.58^{+0.23}_{-0.10}$. We have established that the mode $B^0 \rightarrow \phi K_S^0 \gamma$ can be used at future high luminosity $e^+ e^-$ [3, 4] and hadronic facilities [3] to perform time-
dependent CP violation measurements and to carry out sensitive tests for NP.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and SINET3 network support. We acknowledge support from MEXT, JSPS and Nagoya’s TLPRC (Japan); ARC and DIISR (Australia); NSFC (China); MSMT (Czechia); DST (India); MEST, NRF, NSDC of KISTI, and WCU (Korea); MNiSW (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

[1] D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. 79, 185 (1997). D. Atwood, T. Gershon, M. Hazumi and A. Soni, Phys. Rev. D 71, 076003 (2005).

[2] T. Aushev et al., arXiv:1002.5012. S. Hashimoto et al., Letter of intent for KEK Super B Factory, KEK Report No. KEK-REPORT-2004-4, 2004.

[3] B. O’Leary et al., arXiv:1008.1541.

[5] Y. Ushiroda et al. (Belle Collaboration), Phys. Rev. Lett. 94, 231601 (2005).

[6] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 78, 071102 (2008).

[7] V. D. Orlovsky and V. I. Shevchenko, Phys. Rev. D 77, 093003 (2008). D. Atwood, T. Gershon, M. Hazumi and A. Soni, hep-ph/0701021.

[8] A. Drutskoy et al. (Belle Collaboration), Phys. Rev. Lett. 92, 051801 (2004).

[9] B. Aubert et al. (BaBar Collaboration), Phys. Rev. D 75, 051102 (2007).

[10] Throughout this Letter, the inclusion of the charge-conjugate decay mode is implied unless otherwise stated.

[11] A. Abashian et al. (Belle Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A 479, 117 (2002).

[12] S. Kurokawa and E. Kikutani, Nucl. Instrum. Methods Phys. Res., Sect. A 499, 1 (2003), and other papers included in this volume.

[13] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010).

[14] K.-F. Chen et al. (Belle Collaboration), Phys. Rev. D 72, 012004 (2005).

[15] P. Koppenburg et al. (Belle Collaboration), Phys. Rev. Lett. 93, 061803 (2004).

[16] R. O. Duda, P. E. Hart and D. G. Stork, Pattern Classification, 2nd Edition (John Wiley and Sons, 2001).

[17] T. Skwarnicki, Ph.D. thesis, Institute for Nuclear Physics, Krakow (DESY Internal Report, DESY F31-86-02, 1986). The function is widely used to describe asymmetric distributions caused by shower leakage in crystal calorimeters.

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

[19] \( f(\Delta E, M_{bc}) = [G_1(\Delta E - E_1) + G_2(\Delta E - E_2)] G(M_{bc} - M_0) \), where \( G_1, G_2 \) and \( G \) are Gaussian functions and \( E_1, E_2 \) and \( M_0 \) are constants.

[20] C. H. Chen et al. (Belle Collaboration), Phys. Rev. D 72, 012004 (2005) and private communication with H.-n. Li. The pQCD model is in qualitative agreement with our data after including the kinematic effect of the kaon mass.

[21] H. Kakuno et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 516 (2004).

[22] H. Tajima et al., Nucl. Instrum. Methods Phys. Res., Sect. A 533, 370 (2004).

[23] Private communication with A. Soni.

[24] F. James and M. Roos, Comput. Phys. Commun. 10, 343 (1975).

[25] The MINOS errors are \( \pm 0.32 \) on \( S \) and \( \pm 0.45 \) on \( A \) for data, while the toy MC distributions with input values equal to those measured in data have a width of \( \pm 0.72 \) for \( S \) and \( \pm 0.58 \) for \( A \). The correlation between \( S \) and \( A \) is found to be 0.009 in data.

[26] K. Abe et al. (Belle Collaboration), Phys. Rev. D 68, 012001 (2003).

[27] O. Long, M. Baak, R. N. Cahn and D. Kirkby, Phys. Rev. D 68, 034010 (2003).