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Observation of Radiative $B^0 \to \phi K^0 \gamma$ Decays and Measurements of Their Time-Dependent CP Violation

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We report the first observation of the radiative decay $B^0 \to \phi K^0 \gamma$ using a data sample of 772×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We observe a signal of 35 ± 8 events with a significance of 5.4 standard deviations including systematic uncertainties. The measured branching fraction is $\mathscr{B}(B^0 \to \phi K^0 \gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively. We also report the first measurement of time-dependent CP violation parameters: $\mathscr{S}_{\phi K_S^0 \gamma} = +0.74^{+0.72}_{-1.05}(\mathrm{stat})^{+0.10}_{-0.24}(\mathrm{syst})$ and $\mathscr{A}_{\phi K_S^0 \gamma} = +0.35 \pm 0.58(\mathrm{stat})^{+0.23}_{-0.10}(\mathrm{syst})$. We also precisely measure $\mathscr{B}(B^+ \to \phi K^+ \gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$. The observed $M_{\phi K}$ mass spectrum differs significantly from that expected in a three-body phase-space decay.

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Rare radiative B meson decays play an important role in the search for physics beyond the standard model (SM). These decays are forbidden at tree level in the SM, but allowed through electroweak loop processes. The loop can be mediated by non-SM particles, and therefore is sensitive to new physics (NP). Exclusive $b \to s\gamma$ decays have been extensively measured, but their total sum so far accounts only for 44% of the inclusive rate. Therefore, further measurements of branching fractions for exclusive $B \to \phi K \gamma$ modes will improve our understanding of the $b \to s\gamma$ process. The emitted photons are predominantly left-handed (right-handed) in $b \to s\gamma$ ($\bar{b} \to \bar{s}\gamma$) decays. This suppresses the CP asymmetry in the SM by the quark mass ratio $(2m_s/m_b)$. The expected mixing-induced CP asymmetry parameter ($\mathscr{S}$) is $\mathscr{O}(3\%)$ and the direct CP asymmetry parameter ($\mathscr{A}$) is $\sim 0.6\%$ [1]. However, in several extensions of the SM, both the photon helicities might contribute to the decay. Therefore, any significantly larger CP asymmetry would be clear evidence for NP.

In this presentation, we report the first observation of neutral mode $B^0 \to \phi K^0 \gamma$ [2], the first measurements of time-dependent CP violation in this mode, as well as improved measurements in $B^+ \to \phi K^+ \gamma$ using a data sample of 772×10^6 $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector [3] at the KEKB asymmetric-energy e^+e^- (3.5 on 8.0 GeV) collider [4]. This data sample is nearly eight times larger than the sample used in our previous measurement [5]. In the decay chain $\Upsilon(4S) \to B^0\overline{B}^0 \to f_{\rm rec} f_{\rm tag}$, where one of the B mesons decays at time $t_{\rm rec}$ to the signal mode $f_{\rm rec}$ and the other decays at time $t_{\rm tag}$ to a final state $f_{\rm tag}$ that distinguishes between B^0 and $\overline{B}^0$, the decay rate has a time dependence given by

$$\mathscr{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[\mathscr{S} \sin(\Delta m_d \Delta t) + \mathscr{A} \cos(\Delta m_d \Delta t) \right] \right\}. \tag{1}$$

Here τ_{B^0} is the neutral B lifetime, Δm_d is the mass difference between the two neutral B mass eigenstates, $\Delta t = t_{\rm rec} - t_{\rm tag}$, and the b-flavor charge q equals $+1$ (-1) when the tagging B meson is a B^0 ($\overline{B}^0$).

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 $K_S^0 \to \pi^+\pi^-$. The invariant mass of the kaon pairs from ϕ is required to be within $\left|M_{K^+K^-} - m_\phi\right| < 0.01$ GeV/c^2, where m_ϕ denotes the ϕ meson world-average mass [6]. The K_S^0 selection criteria are the same as those described in the Ref. [7]; the invariant mass of the pion pairs is required to satisfy $M_{\pi^+\pi^-} \in (0.482, 0.514)$ GeV/c^2. The high energy prompt photons are selected from isolated clusters within the barrel region of the calorimeter and center-of-mass system (cms) energy, $E_\gamma^{\rm cms} \in (1.4, 3.4)$ GeV. B candidates are identified using two kinematic variables: the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$ and the beam-energy-constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where $E_{\rm beam}^{\rm cms}$ is the beam energy in the cms, and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum, respectively, of the reconstructed B candidate. In the $M_{\rm bc}$ calculation, the photon momentum is replaced by $(E_{\rm beam}^{\rm cms} - E_{\phi K}^{\rm cms})$ to improve its resolution. The candidates that satisfy the requirements $M_{\rm bc} > 5.2$ GeV/c^2 and $|\Delta E| < 0.3$ GeV are selected for further analysis.

The dominant background is from the continuum process, which is suppressed by a requirement on likelihood ratio ($\mathscr{R}$) from event shape variables and the B flight direction. We require $\mathscr{R} > 0.65$, which removes 91% of the continuum while retaining 76% of the signal. In the $B^0 \to \phi K_S^0 \gamma$ mode, some backgrounds from $b \to c$ decays, such as $D^0\pi^0$, $D^0\eta$ and $D^-\rho^+$ peak in the $M_{\rm bc}$ distribution. We remove the dominant peaking backgrounds by applying a veto to ϕK_S^0 combinations consistent with the nominal D mass [6]. Some of the charmless backgrounds, where

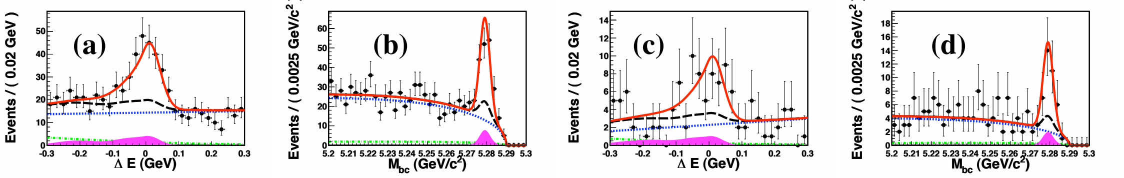

Figure 1: The ΔE and $M_{\rm bc}$ projections for $B^+ \to \phi K^+ \gamma$ ((a) and (b)) and $B^0 \to \phi K_S^0 \gamma$ ((c) and (d)). The points with error bars represent the data. The curves show the total fit function (solid red), total background function (long-dashed black), continuum component (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 B meson decays to $\phi K^*(892)$, $\phi K \pi^0$ and $\phi K \eta$ also peak in $M_{\rm bc}$, but shift towards lower ΔE. Another significant background is non-resonant $B \to K^+ K^- K \gamma$, which peaks in the ΔE-$M_{\rm bc}$ signal region; it is estimated using the ϕ mass sideband $M_{K^+K^-} \in (1.05, 1.3)$ GeV/c^2, in data.

The signal yield is obtained from an extended unbinned maximum-likelihood (UML) fit to the two-dimensional ΔE-$M_{\rm bc}$ distribution as shown in Fig. 1. The probability density functions (PDFs) for different components and fitting procedure are described in detail elsewhere [8]. The fit yields a signal of 136 ± 17 $B^+ \to \phi K^+ \gamma$ and 35 ± 8 $B^0 \to \phi K_S^0 \gamma$ candidates. The signal in the charged mode has a significance of 9.6σ, whereas that for the neutral mode is 5.4σ, including systematic uncertainties. The observed ϕK mass spectrum differs significantly from that expected in a three-body phase-space decay. Nearly 72% of the signal events are concentrated in the low-mass region ($M_{\phi K} \in (1.5, 2.0)$ GeV/c^2). The Monte Carlo (MC) efficiency after reweighting according to this $M_{\phi K}$ dependence is $(15.3 \pm 0.1)\%$ for the charged and $(10.0 \pm 0.1)\%$ for the neutral mode. We measure the branching fraction as $\mathscr{B}(B^+ \to \phi K^+ \gamma) = (2.34 \pm 0.29 \pm 0.23) \times 10^{-6}$ and $\mathscr{B}(B^0 \to \phi K^0 \gamma) = (2.66 \pm 0.60 \pm 0.32) \times 10^{-6}$, where the uncertainties are statistical and systematic, respectively.

For the CP asymmetry fit, we select events that satisfy $M_{\rm bc} \in (5.27, 5.29)$ GeV/c^2 and $\Delta E \in (-0.2, 0.1)$ GeV. The vertex position for the $f_{\rm rec}$ decay is reconstructed using the two kaon tracks from ϕ meson and that of $f_{\rm tag}$ decay is from well-reconstructed tracks that are not assigned to $f_{\rm rec}$ [9]. We then use a flavor tagging algorithm [10] to obtain q and the tagging quality factor $r \in (0, 1)$. The typical vertex reconstruction efficiency (z resolution) is 96% (115 μm) for $f_{\rm rec}$ and 94% (104 μm) for $f_{\rm tag}$. After all selection criteria are applied, we obtain 75 (436) events for the CP fit with a purity of 45% (35%) in the neutral (charged) mode. The signal PDF is given by a modified form of Eq. (1) by fixing τ_{B^0} and Δm_d to their world-average values [6] and incorporating the effect of incorrect flavor assignment. Since the non-resonant component has the same NP as the signal $B \to \phi K \gamma$, we treat this as signal. The only free parameters in the CP fit are $\mathscr{S}$ and $\mathscr{A}$, which are determined to be $\mathscr{S}_{\phi K_S^0 \gamma} = +0.74^{+0.72}_{-1.05}(\text{stat})^{+0.10}_{-0.24}(\text{syst})$ and $\mathscr{A}_{\phi K_S^0 \gamma} = +0.35 \pm 0.58(\text{stat})^{+0.23}_{-0.10}(\text{syst})$. We define the raw asymmetry in each Δt bin by $(N_+ - N_-)/(N_+ + N_-)$, where N_+ (N_-) is the number of observed candidates with $q = +1$ (-1). Figure 2 shows the Δt distributions and raw asymmetry for events with good tagging quality ($r > 0.5$, 48% of total). We find that the error on $\mathscr{S}$ in the MINUIT minimization is much smaller than the expectation from MC simulation and has a probability of only 0.6% [11]. This is due to low statistics and the presence of a single special event. Instead, we use the $\pm 68\%$ confidence intervals in the residual distributions of $\mathscr{S}$ and $\mathscr{A}$, determined from the toy MC as the uncertainties for the final result.

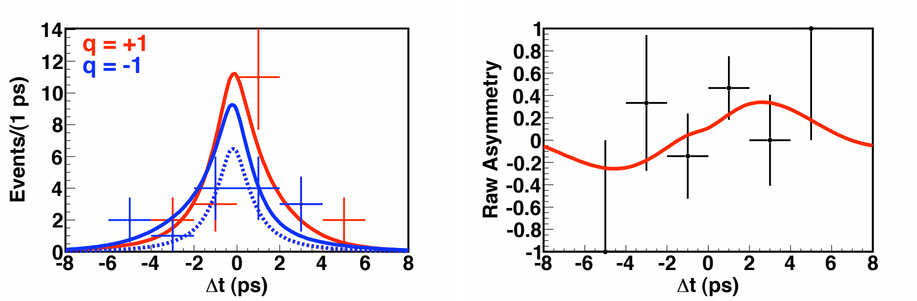

Figure 2: Δt distributions for $q = +1$ and $q = -1$ (left) and the raw asymmetry (right) for well-tagged events. The dashed curves in the Δt plot are the sum of backgrounds while the solid curves are the sum of signal and backgrounds. The solid curve in asymmetry plot shows the result of the UML fit.

In summary, we report the first observation of radiative $B^0 \to \phi K^0 \gamma$ decays using a data sample of 772×10^6 $B\overline{B}$ pairs. The observed signal yield is 35 ± 8 with a significance of $5.4\,\sigma$. We also report the first measurements of time-dependent CP violation parameters in this mode: $\mathscr{S} = 0.74^{+0.72+0.10}_{-1.05-0.24}$ and $\mathscr{A} = 0.35 \pm 0.58^{+0.23}_{-0.10}$. We precisely measure branching fraction and charge asymmetry ($\mathscr{A}_{CP} = -0.03 \pm 0.11 \pm 0.08$) in the charged mode. The signal events are mostly concentrated at low ϕK mass, which is similar to a two-body radiative decay. With the present statistics, these measurements are consistent with the SM predictions and there is no indication of NP from right-handed currents in radiative B decays. Much more luminosity is necessary for a precise test of the SM.

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[11] The MINOS errors are ${}^{+0.32}_{-0.45}$ for $\mathscr{S}$ and ± 0.45 for $\mathscr{A}$. The toy MC distributions has a width of ${}^{+0.72}_{-1.05}$ for $\mathscr{S}$ and ± 0.58 for $\mathscr{A}$.