Observation of $B \to K^* \ell^+ \ell^-$

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We report the observation of the flavor-changing neutral current decay $B \to K^* \ell^+ \ell^-$ and an improved measurement of the decay $B \to K \ell^+ \ell^-$, where ℓ represents an electron or a muon, with a data sample of 140 fb^{-1} accumulated at the $\Upsilon(4S)$ resonance with the Belle detector at KEKB. The results for the branching fractions are $\mathcal{B}(B \to K^* \ell^+ \ell^-) = (11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2) \times 10^{-7}$ and $\mathcal{B}(B \to K \ell^+ \ell^-) = (4.8^{+1.0}_{-0.9} \pm 0.3 \pm 0.1) \times 10^{-7}$, where the first error is statistical, the second is systematic and the third is from model dependence.

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Flavor-changing neutral current (FCNC) processes are forbidden at tree level in the standard model (SM); they proceed only at a low rate via higher-order loop diagrams. SM decay amplitudes for the FCNC processes $B \to X_s \gamma$ and $B \to X_s \ell^+ \ell^-$, where X_s denotes inclusive hadronic final states with a strangeness $S = \pm 1$ and ℓ represents an electron or a muon, have been calculated with small errors [1]. If additional diagrams with non-SM particles contribute to these FCNC processes, their amplitudes will interfere with the SM amplitudes, making these processes ideal places to search for new physics [2].

Measurements of the decay rate for $B \to X_s \gamma$ [3] as well as the recent first exclusive and inclusive measurements by Belle for $B \to K \ell^+ \ell^-$ [4] and $B \to X_s \ell^+ \ell^-$ [5] have so far shown no disagreement with the SM predictions. Deviations due to non-SM amplitudes are often expressed in terms of Wilson coefficients C_7, C_9, and C_{10}; a strong constraint on the magnitude of C_7 has been set by $B \to X_s \gamma$, and a large area of the C_9–C_{10} plane has been excluded by $B \to K \ell^+ \ell^-$ and $B \to X_s \ell^+ \ell^-$ [6]. A complete determination of all three Wilson coefficients, including the sign of C_7, requires the measurement of the forward-backward asymmetry in $B \to K^* \ell^+ \ell^-$ or $B \to X_s \ell^+ \ell^-$; however, $B \to K^* \ell^+ \ell^-$ has not been previously observed [4,7]. A typical recent calculation gives $\mathcal{B}(B \to K^* \ell^+ \ell^-) = (11.9 \pm 3.9) \times 10^{-7}$ [6] in the SM.

In this Letter, we report the observation of $B \to K^* \ell^+ \ell^-$, using a data sample of 152×10^6 $B\overline{B}$ pairs, corresponding to 140 fb^{-1} taken at the $\Upsilon(4S)$ resonance. We also report an improved measurement of $B \to K \ell^+ \ell^-$, superseding our previous result based on 29 fb^{-1} [4].

The data are collected with the Belle detector [8] at the KEKB energy-asymmetric e^+e^- (3.5 on 8 GeV) collider [9]. The Belle detector consists of a silicon vertex detector, a central drift chamber (CDC), aerogel Cherenkov counters (ACC), time-of-flight (TOF) scintillation counters, and a CsI(Tl) electromagnetic calorimeter (ECL) located inside a superconducting solenoid coil. An iron flux-return located outside of the coil is instrumented to identify muons (KLM).

We reconstruct the following final states: $B^0 \to K^{*0} \ell^+ \ell^-$, $B^+ \to K^{*+} \ell^+ \ell^-$, $B^0 \to K^0_S \ell^+ \ell^-$, and $B^+ \to K^+ \ell^+ \ell^-$. Charge conjugate modes are implied throughout this Letter. The following decay chains are used to reconstruct the intermediate states: $K^{*0} \to K^+\pi^-$, $K^{*+} \to K_S^0\pi^+$ and $K^+\pi^0$, $K_S^0 \to \pi^+\pi^-$, and $\pi^0 \to \gamma\gamma$.

Charged tracks are classified as e, μ, K, and π candidates by discriminating between the flavors for the pairwise combinations. The e/h discriminant (where $h = K$ or π) is formed from the energy deposit in the ECL, the specific ionization measurements in the CDC, and the ACC light yield. The μ/h discriminant is based on the hits in the KLM. The K/π and K/μ discriminants use the CDC, ACC, and TOF information. Each track can have more than one flavor assignment. Specifically, a track is classified as a pion unless it satisfies tight requirements on either the K/π, e/h, or μ/h discriminant, and a non-pion-like kaon can *also* be classified as an electron if it satisfies the loose criteria on the e/h discriminant or, perhaps, also as a muon if it satisfies the tight criteria on the μ/h discriminant. To reduce the misidentification of hadrons as leptons, we require minimum momenta of 0.4 and 0.7 GeV$/c$ for electrons and muons, respectively, and specify the cut on the μ/h discriminant according to whether the track momentum is above or below 1.0 GeV$/c$. Each of the charged tracks, except for the $K_S^0 \to \pi^+\pi^-$ daughters, is required to have an impact parameter with respect to the interaction point of less than 0.5 cm transverse to, and 5.0 cm along the positron beam axis. Photons are reconstructed within the ECL with a minimum energy requirement of 50 MeV.

Invariant masses for the π^0, K_S^0, and K^* candidates are required to be within ± 10 MeV$/c^2$ (2σ), ± 15 MeV$/c^2$ (3.3σ), and ± 75 MeV$/c^2$, respectively, of their nominal masses. We require a minimum momentum of 0.1 GeV$/c$ for the π^0 candidates. We impose K_S^0 selection criteria based on the distance and the direction of the K_S^0 vertex and the impact parameters of daughter tracks. For $K^{*+} \to K^+\pi^0$, $\cos\theta_{\rm hel} < 0.8$ is required to reduce background from soft $\pi^0 s$, where $\theta_{\rm hel}$ is the angle between the K^{*+} momentum in the B rest frame and the K^+ momentum in the K^{*+} rest frame.

We form B candidates by combining a $K^{(*)}$ candidate and an oppositely charged lepton pair using two variables: the beam-energy constrained mass $M_{\rm bc} = \sqrt{(E^*_{\rm beam}/c^2)^2 - |p^*_B/c|^2}$ and the energy difference $\Delta E = E^*_B - E^*_{\rm beam}$, where p^*_B and E^*_B are the measured momentum and energy, respectively, of the B candidate, and $E^*_{\rm beam}$ is the beam energy. Throughout this Letter, variables denoted with an asterisk are calculated in the $\Upsilon(4S)$ rest frame. When multiple candidates are found in an event, we select the candidate with the smallest value of $|\Delta E|$.

The following five types of backgrounds are considered: (i) *Charmonium B* decay background from $B \to J/\psi(\psi')X$ decays is removed by vetoing lepton pairs whose invariant mass is near the $J/\psi(\psi')$ mass [4]. In addition, we reject events that have a photon with energy less than 500 MeV within a 50 mrad cone around either the electron or positron direction (or a photon within each cone) and an $e^+e^-\gamma(\gamma)$ invariant mass within the veto windows. For $K^*\ell^+\ell^-$ modes, we reject the event if an unobserved photon along one of the lepton directions with an energy $E^*_{\rm beam} - E^*_K - E^*_{\ell\ell}$ can replace the pion, giving $M_{\ell\ell\gamma}$ and $M_{\rm bc}$ consistent with $J/\psi K$. (ii) We suppress background from *photon conversions* and $\pi^0 \to e^+e^-\gamma$ by requiring the dielectron mass to satisfy $M_{ee} > 0.14$ GeV$/c^2$. This eliminates possible background from $B \to K^*\gamma$ and $K^{(*)}\pi^0$. (iii) Background from *continuum* $q\bar{q}$ is suppressed using a likelihood ratio $\mathcal{R}_{\rm cont}$ formed from a Fisher discriminant, $\cos\theta^*_B$, and, for $K^{(*)}e^+e^-$ only, $\cos\theta^*_{\rm sph}$. The Fisher discriminant [10] is calculated from the energy flow in 9 cones along the B candidate sphericity axis and the normalized second Fox-Wolfram moment R_2 [11]. The angles θ^*_B and $\theta^*_{\rm sph}$ are measured between the beam axis and the B meson direction and sphericity axis, respectively. (iv) *Semileptonic B* decay background is suppressed using another likelihood ratio $\mathcal{R}_{\rm sl}$, formed from the missing energy of the event and $\cos\theta^*_B$. (v) *Hadronic B* decay background, $B \to K^{(*)}h^+h^-$, e.g., from $B \to D\pi$, can contribute if two hadrons are misidentified as leptons. We find that other potential backgrounds are negligible except for nonresonant $B \to K\pi\ell^+\ell^-$ decay. We assume no $K\pi\ell^+\ell^-$.

For each decay mode, the selection criteria on the two likelihood ratios $\mathcal{R}_{\rm cont}$ and $\mathcal{R}_{\rm sl}$ are chosen to maximize $N_S/\sqrt{N_S + N_B}$, where N_S is the expected signal yield and N_B is the expected background in the $M_{\rm bc}$ and ΔE signal windows. The signal windows (2.5σ) are defined as $|M_{\rm bc} - M_B| < 0.007$ GeV$/c^2$ for both lepton modes and $-0.055(-0.035)$ GeV $< \Delta E < 0.035$ GeV for the electron (muon) mode. A large Monte Carlo (MC) background sample of a mixture of $b \to c$ decays and $e^+e^- \to q\bar{q}$ events is used to estimate N_B. The $K^{(*)}\ell^+\ell^-$ signal events are generated according to Ref. [6] to determine N_S, and to estimate the efficiencies that are summarized in Table I.

The signal yield is determined by a binned maximum-likelihood fit to the $M_{\rm bc}$ distribution for the events within the ΔE signal window using a Gaussian signal plus three background functions. The mean and width of this Gaussian are determined using observed $J/\psi K^{(*)}$ events. We find no dilepton mass dependence of the width and mean using a MC study. The first background function is for the semileptonic B decays and, to a lesser extent, the continuum background, and is modeled with a threshold function [12] whose shape parameter is determined using a large MC sample that contains oppositely charged leptons and whose normalization is floated. This MC sample reproduces the background parametrization for $K^{(*)}e^\pm\mu^\mp$ data in which only combinatorial background is expected. The two other background functions account for the residual B to charmonium decays and hadronic B decays, and are modeled with separate combinations of a similar threshold function and an additional Gaussian

TABLE I. Summary of the results: signal yields obtained from the M_{bc} fit and their significances, reconstruction efficiencies including the intermediate branching fractions, branching fractions ($\mathcal{B}$), and their 90% confidence level upper limits.

Mode	Signal yield $\pm$stat $\pm$ syst	Significance	Efficiency [%] $\pm$stat $\pm$ model	$\mathcal{B}$ [$\times 10^{-7}$] $\pm$stat $\pm$ syst$\pm$model	Upper Limit [$\times 10^{-7}$]
$K^{*0}e^+e^-$	$10.2^{+4.5}_{-3.8} \pm 0.8$	2.8	$5.2 \pm 0.3 \pm 0.04$	$12.9^{+5.7}_{-4.9} \pm 1.1 \pm 0.1$	24
$K^{*+}e^+e^-$	$5.3^{+3.3+0.5}_{-2.6-0.6}$	1.9	$1.7 \pm 0.1 \pm 0.1$	$20.2^{+12.7+2.3}_{-10.1-2.4} \pm 0.7$	46
$K^*e^+e^-$	$15.6^{+5.5}_{-4.8} \pm 1.0$	3.5	$3.5 \pm 0.2 \pm 0.04$	$14.9^{+5.2+1.2}_{-4.6-1.3} \pm 0.2$	
$K^0e^+e^-$	$0.0^{+1.5+0.2}_{-0.9-0.3}$	0.0	$5.0 \pm 0.3 \pm 0.1$	$0.0^{+2.0+0.3}_{-1.2-0.4} \pm 0.0$	5.4
$K^+e^+e^-$	$15.9^{+4.9}_{-4.2} \pm 0.6$	5.1	$16.6 \pm 0.7 \pm 0.4$	$6.3^{+1.9}_{-1.7} \pm 0.3 \pm 0.1$	
Ke^+e^-	$15.9^{+5.1}_{-4.4} \pm 0.7$	4.5	$10.8 \pm 0.5 \pm 0.2$	$4.8^{+1.5}_{-1.3} \pm 0.3 \pm 0.1$	
$K^{*0}\mu^+\mu^-$	$17.1^{+5.4}_{-4.7} \pm 0.9$	4.2	$8.5 \pm 0.5 \pm 0.3$	$13.3^{+4.2}_{-3.7} \pm 1.0 \pm 0.5$	
$K^{*+}\mu^+\mu^-$	$2.8^{+2.9}_{-2.3} \pm 0.6$	0.8	$2.8 \pm 0.2 \pm 0.2$	$6.5^{+6.9+1.4}_{-5.3-1.5} \pm 0.4$	22
$K^*\mu^+\mu^-$	$20.0^{+6.0+1.1}_{-5.3-1.2}$	4.2	$5.6 \pm 0.3 \pm 0.2$	$11.7^{+3.6}_{-3.1} \pm 0.9 \pm 0.5$	
$K^0\mu^+\mu^-$	$5.7^{+3.0+0.2}_{-2.3-0.3}$	3.1	$6.7 \pm 0.4 \pm 0.3$	$5.6^{+2.9}_{-2.3} \pm 0.4 \pm 0.3$	
$K^+\mu^+\mu^-$	$16.3^{+5.1+0.7}_{-4.5-0.8}$	4.6	$23.6 \pm 1.1 \pm 0.6$	$4.5^{+1.4}_{-1.2} \pm 0.3 \pm 0.1$	
$K\mu^+\mu^-$	$22.0^{+5.8}_{-5.1} \pm 0.8$	5.6	$15.2 \pm 0.7 \pm 0.5$	$4.8^{+1.2}_{-1.1} \pm 0.3 \pm 0.2$	
$K^{*0}\ell^+\ell^-$	$27.4^{+6.9}_{-6.2} \pm 1.3$	5.2	$7.7 \pm 0.4 \pm 0.2$	$11.7^{+3.0}_{-2.7} \pm 0.8 \pm 0.3$	
$K^{*+}\ell^+\ell^-$	$8.1^{+4.3+0.8}_{-3.3-0.9}$	2.1	$2.5 \pm 0.2 \pm 0.05$	$10.5^{+5.6+1.2}_{-4.3-1.1} \pm 0.2$	22
$K^*\ell^+\ell^-$	$35.8^{+8.0}_{-7.3} \pm 1.7$	5.7	$5.1 \pm 0.3 \pm 0.1$	$11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2$	
$K^0\ell^+\ell^-$	$5.7^{+3.4+0.4}_{-2.7-0.5}$	2.3	$5.9 \pm 0.4 \pm 0.2$	$3.2^{+1.9}_{-1.5} \pm 0.3 \pm 0.1$	6.8
$K^+\ell^+\ell^-$	$32.3^{+6.9+0.9}_{-6.2-1.0}$	7.0	$20.1 \pm 0.9 \pm 0.1$	$5.3^{+1.1}_{-1.0} \pm 0.3 \pm 0.04$	
$K\ell^+\ell^-$	$37.9^{+7.6+1.0}_{-6.9-1.1}$	7.4	$13.0 \pm 0.6 \pm 0.2$	$4.8^{+1.0}_{-0.9} \pm 0.3 \pm 0.1$	

component. The shape and the size of the charmonium background function are fixed from J/ψ and ψ' inclusive MC samples. We find the Gaussian component of the charmonium background contributes less than one event. The shape and the size of the hadronic background are evaluated using hadron enriched data by relaxing the lepton identification criteria. The Gaussian components of the hadronic background contribution, multiplied by the lepton misidentification probability (measured in bins of momentum and polar angle with respect to the positron beam), are then found to be 1.05 ± 0.08 and 0.64 ± 0.05 events for $K\ell^+\ell^-$ and $K^*\ell^+\ell^-$, respectively.

Figure 1 and Table I give the fit results. We observe $35.8^{+8.0}_{-7.3}(\mathrm{stat}) \pm 1.7(\mathrm{syst})$ $K^*\ell^+\ell^-$ signal events with a significance of 5.7, and $37.9^{+7.6}_{-6.9}(\mathrm{stat})^{+1.0}_{-1.1}(\mathrm{syst})$ $K\ell^+\ell^-$ signal events with a significance of 7.4. The error due to uncertainty in the fixed parameters is included in the systematic error. To evaluate the uncertainty in the signal function parametrization, the mean and width of the Gaussian are changed by $\pm 1\sigma$. The uncertainty in the semileptonic plus continuum background parametrization, which is the largest error source, is obtained by varying the parameter by $\pm 1\sigma$. The uncertainties of the hadronic (charmonium) background contributions are evaluated by changing the shape parameters and the normalizations of the Gaussian and threshold components by $\pm 1\sigma$ ($\pm 100\%$). The significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\max})}$, where $\mathcal{L}_{\max}$ is the maximum likelihood in the M_{bc} fit and $\mathcal{L}_0$ is the likelihood of the best fit when the signal yield is constrained to be zero. In order to include the effect of systematic error in the significance calculation, we use the parameters simultaneously changed by 1σ (100% for the charmonium background) in the direction that reduces the resulting significance.

In addition to the systematic error in the signal yield, we consider the following experimental systematic errors in the efficiency determination. For each charged track, we estimate the systematic error due to reconstruction efficiency to be 1.0%, and the systematic errors due to kaon, pion, electron, and muon identification to be 1.0%, 0.8%, 0.5%, and 1.2%, respectively. For each K_S^0 candidate and π^0 candidate, we estimate the systematic errors due to reconstruction efficiencies to be 4.5% and 2.7%, respectively. The uncertainty in the background suppression is estimated to be 2.3% using $J/\psi K^{(*)}$ control samples. Systematic errors due to MC statistics range from 0.5% to 2.2%. All these errors are added in quadrature.

The uncertainty in the SM assumptions is evaluated by calculating the efficiency for signal MC samples generated using three form-factor models [6,13] and taking the maximum difference as the model-dependence error.

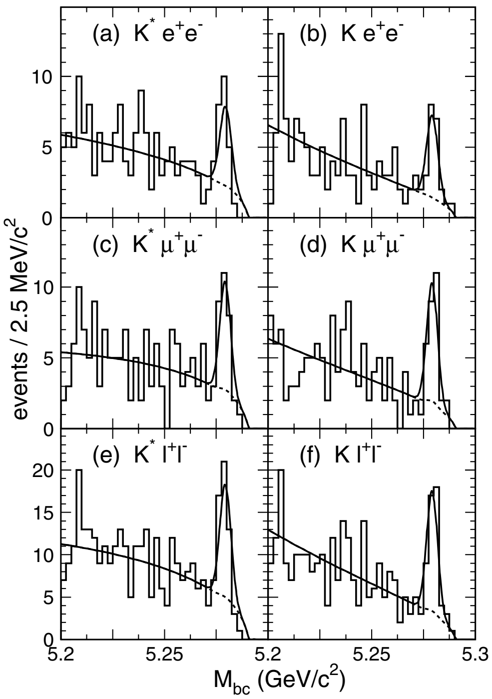

FIG. 1. $M_{\rm bc}$ distributions (histograms) for $K^{(*)}\ell^+\ell^-$ samples. Solid and dotted curves show the results of the fits and the background contributions, respectively.

When calculating the branching fractions, we assume an equal production rate for charged and neutral B meson pairs, isospin invariance, lepton universality for $K\ell^+\ell^-$, and the branching ratio $\mathcal{B}(B \to K^* e^+ e^-)/\mathcal{B}(B \to K^* \mu^+ \mu^-) = 1.33$ [6]. The combined efficiency and branching fraction are scaled to the muon mode. We find

$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (11.5^{+2.6}_{-2.4} \pm 0.8 \pm 0.2) \times 10^{-7},$$

$$\mathcal{B}(B \to K\ell^+\ell^-) = (4.8^{+1.0}_{-0.9} \pm 0.3 \pm 0.1) \times 10^{-7},$$

where the first error is statistical, the second is systematic, and the third is from model dependence. This systematic error is a quadratic sum of the systematic errors in the yield and efficiency, and the uncertainty in B meson pair counting of 0.5%. The results are within the ranges of predicted SM values [6,13,14] and previous measurements and upper limits [4,7]. The complete set of results is given in Table I.

For the modes with a significance of less than 3, we set 90% confidence level upper limits. The upper limit on the yield, N, is defined as $\int_0^N \mathcal{L}(n)dn = 0.9 \int_0^\infty \mathcal{L}(n)dn$. The function $\mathcal{L}(n)$ is the likelihood for signal yield n, using signal and background shape parameters that are modified by 1σ of their errors in the direction to increase the signal yield. The upper limits for the branching fractions are then calculated by using the efficiencies reduced by 1σ of their errors.

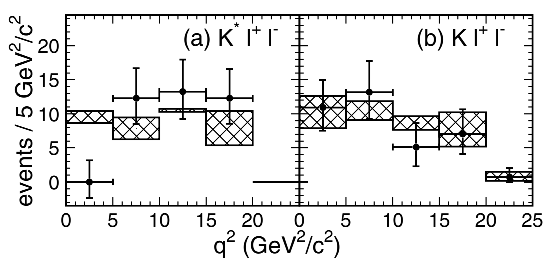

FIG. 2. q^2 distributions of $K^{(*)}\ell^+\ell^-$. Points with error bars show the data while the hatched boxes show the range of SM expectations from various models [6,13]. Statistical and systematic errors are added in quadrature.

Figure 2 shows the measured $q^2 = M_{\ell\ell}^2 c^2$ distributions for $K\ell^+\ell^-$ and $K^*\ell^+\ell^-$. The signal yield is extracted in each q^2 bin from a fit to the $M_{\rm bc}$ distributions.

In summary, we have observed the decay $B \to K^*\ell^+\ell^-$. This mode will provide a useful sample for a forward-backward asymmetry measurement. The $B \to K\ell^+\ell^-$ decay is also measured with improved accuracy. The measured branching fractions are in agreement with the SM predictions, and may be used to provide more stringent constraints on physics beyond the SM.

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