Measurement of Forward-Backward Asymmetry and Wilson Coefficients in $B \to K^* l^+ l^-$

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We report the first measurement of the forward-backward asymmetry and the ratios of Wilson coefficients A_9/A_7 and A_{10}/A_7 in $B \to K^* \ell^+ \ell^-$, where ℓ represents an electron or a muon. We find evidence for the forward-backward asymmetry with a significance of 3.4σ. The results are obtained from a data sample containing 386×10^6 $B\bar{B}$ pairs that were collected on the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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Flavor-changing neutral current $b \to s$ processes proceed via loop diagrams in the standard model (SM). If additional diagrams with non-SM particles contribute to such processes, the decay rate and kinematics are modified. Such contributions may change the 12 Wilson coefficients [1] that parametrize the strength of the weak and strong short distance interactions. The $b \to s\ell^+\ell^-$ amplitude is described by the effective Wilson coefficients C_7, C_9, and C_{10}, whose terms have been calculated up to next-to-next-to-leading order (NNLO) [2] in quantum chromodynamics. To evaluate the Wilson coefficients, we use A_i which are dominant and q^2-independent real terms of C_i. Other small complex terms in C_i are fixed to the SM values. Here, q^2 is the squared invariant mass of the dilepton system.

The magnitude of A_7 is strongly constrained from measurements of $B \to X_s\gamma$ [3,4], where X_s is a hadronic system with an s quark; a large area of the (A_9, A_{10}) plane is excluded by branching fraction measurements of $B \to X_s\ell^+\ell^-$ and $B \to K^{(*)}\ell^+\ell^-$ [5–8], where $K^{(*)}$ refers to K or K^*. However, the sign of A_7 and the values of A_9 and A_{10} are not yet determined. Measurement of the forward-backward asymmetry and differential decay rate as functions of q^2 and θ for $B \to K^*\ell^+\ell^-$ constrains the relative signs and magnitudes of these coefficients [9,10]. Here θ is the angle between the momenta of the negative (positive) lepton and the B ($\bar{B}$) meson in the dilepton rest frame. The forward-backward asymmetry is defined using the differential decay width $g(q^2, \theta) = d^2\Gamma/dq^2 d\cos\theta$ [11] as

$$\mathcal{A}_{\rm FB}(q^2) = \frac{\int_{-1}^{1} \mathrm{sgn}(\cos\theta) g(q^2, \theta) d\cos\theta}{\int_{-1}^{1} g(q^2, \theta) d\cos\theta}. \quad (1)$$

The numerator in Eq. (1) can be expressed in terms of Wilson coefficients as

$$\int_{-1}^{1} \mathrm{sgn}(\cos\theta) g(q^2, \theta) d\cos\theta = -C_{10}\xi(q^2) \times \left(\mathrm{Re}(C_9)F_1 + \frac{1}{q^2}C_7F_2\right), \quad (2)$$

where ξ is a function of q^2, while F_1 and F_2 depend on form factors. (The full expression can be found in Ref. [11].)

In this Letter, we report the first measurement of the forward-backward asymmetry and ratios of Wilson coefficients in $B \to K^*\ell^+\ell^-$. We use a 357 fb^{-1} data sample containing 386×10^6 $B\bar{B}$ pairs taken at the $\Upsilon(4S)$ resonance. We also study the $B^+ \to K^+\ell^+\ell^-$ mode, which is expected to have a very small forward-backward asymmetry even in the presence of new physics [12]. Charge-conjugate modes are included throughout this Letter.

The data were taken at the KEKB collider [13] and collected with the Belle detector [14]. The detector consists of a silicon vertex detector, a central drift chamber, aerogel Cherenkov counters, time-of-flight scintillation counters, an electromagnetic calorimeter, and a muon identification system.

The event reconstruction procedure is the same as described in our previous Letter [5]. The following final states are used to reconstruct B candidates: $K^{*0}\ell^+\ell^-$, $K^{*+}\ell^+\ell^-$, and $K^+\ell^+\ell^-$, with subdecays $K^{*0} \to K^+\pi^-$, $K^{*+} \to K^0_S\pi^+$ and $K^+\pi^0$, $K^0_S \to \pi^+\pi^-$, and $\pi^0 \to \gamma\gamma$.

Hereafter, $K^{*0}\ell^+\ell^-$ and $K^{*+}\ell^+\ell^-$ are combined and called $K^*\ell^+\ell^-$.

We use two variables defined in the center-of-mass (c.m.) frame to select B candidates: 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 c.m. momentum and energy of the B candidate, and $E^*_{\rm beam}$ is the c.m. beam energy. When multiple candidates are found in an event, we select the candidate with the smallest value of $|\Delta E|$.

The dominant background consists of $B\bar{B}$ events where both B mesons decay semileptonically. We suppress this background using missing energy and $\cos\theta^*_B$, where θ^*_B is the angle between the flight direction of the B meson and the beam axis in the c.m. frame. These quantities are combined to form signal and background likelihoods $\mathcal{L}_{\rm sig}$ and $\mathcal{L}_{B\bar{B}}$, respectively, and event selection is then performed using the ratio $\mathcal{R}_{B\bar{B}} = \mathcal{L}_{\rm sig}/(\mathcal{L}_{\rm sig} + \mathcal{L}_{B\bar{B}})$. The continuum ($e^+e^- \to q\bar{q}$, $q = u, d, s, c$) background is suppressed using a likelihood ratio $\mathcal{R}_{\rm cont}$ (defined similarly to $\mathcal{R}_{B\bar{B}}$) that depends on three variables: a Fisher discriminant [15] calculated from the sum of c.m. energies of the final state particles in each of nine cones along the B candidate c.m. sphericity axis [16] and the normalized second Fox-Wolfram moment [17], the angle between the beam axis and the c.m. sphericity axis, and $\cos\theta^*_B$. Backgrounds from $B \to J/\psi X_s$ and $B \to \psi(2S)X_s$ decays, referred to below as $B \to \psi X_s$, are rejected using the dilepton invariant mass. Backgrounds from photon conversions and π^0 Dalitz decays are suppressed by requiring the e^+e^- invariant mass to be above 140 MeV$/c^2$.

The signal box is defined as $|M_{\rm bc} - m_B| < 8$ MeV$/c^2$ for both lepton modes and $-55(-35)$ MeV $< \Delta E <$ 35 MeV for the electron (muon) mode. We optimize the selections on $\mathcal{R}_{\rm cont}$ and $\mathcal{R}_{B\bar{B}}$ for each K^* decay mode and each lepton mode to maximize sensitivity to events with $q^2 < 6$ GeV$^2/c^2$ assuming the branching fractions in Ref. [18].

To determine the signal yield, we perform an unbinned maximum-likelihood fit to the $M_{\rm bc}$ distribution for events that lie within the ΔE signal window. The fit function includes signal, cross feeds, and other background components. The cross feeds are misreconstructed $K^{(*)}\ell^+\ell^-$ events with correct ("CF") and incorrect ("IF") B meson flavor assignment. The cross feed from $X_s\ell^+\ell^-$ events other than $K^{(*)}\ell^+\ell^-$ is negligible. The other backgrounds come from dilepton background, combinatorial $K^{(*)}\ell^\pm h^\mp$, $K^{(*)}h^+h^-$, and ψX_s events, where h represents a pion or a kaon. The dilepton background refers to the sum of all background sources with two leptons where the lepton is from leptonic or semileptonic meson decays, photon conversions, and π^0 Dalitz decays. The $K^{(*)}h^+h^-$ background is from both combinatorial background and B meson decays.

The shape for cross-feed events is parametrized by a sum of an ARGUS function [19] and a Gaussian whose parameters are determined from Monte Carlo (MC) samples. The dilepton background is modeled by an ARGUS function. The shape of each background is determined from a MC sample. (The $K^{(*)}e^\pm\mu^\mp$ background shape is found to be consistent between the MC sample and data.) Since the shape for $K^{(*)}\ell^\pm h^\mp$ is similar to that for the dilepton background, we use the same parametrizations for both backgrounds. The residual background from ψX_s is estimated from a MC sample of ψ inclusive events and parametrized by the sum of an ARGUS function and a Gaussian. The background from events with misidentified leptons is also parametrized by the sum of an ARGUS function and a Gaussian. In the fit, all background fractions except the dilepton background are fixed while the signal fraction is allowed to float.

Figure 1 shows the fit result. We obtain 113.6 ± 13.0 and 96.0 ± 12.0 signal events for $K^*\ell^+\ell^-$ and $K^+\ell^+\ell^-$, respectively.

We use $B \to K^*\ell^+\ell^-$ candidates in the signal box to measure the normalized double differential decay width. For the evaluation of the Wilson coefficients, the full (partial) NNLO Wilson coefficients C_i [2,7] are used for $q^2/m_b^2 < 0.25$ (> 0.25). The value of A_7 is fixed at the SM value -0.330 or the sign-flipped value $+0.330$. The SM values for A_9 and A_{10} are 4.07 and -4.21, respectively [7]. We choose A_9/A_7 and A_{10}/A_7 as fit parameters. To extract these ratios, we perform an unbinned maximum-likelihood fit to the events in the signal box with a probability density function (PDF) that includes the normalized double differential decay width. The PDF used for the fit consists of terms describing the signal, cross feeds, and backgrounds:

$$\begin{aligned} P(M_{\rm bc}, q^2, \cos\theta; A_9/A_7, A_{10}/A_7) = {} & \frac{1}{N_{\rm sig}} f_{\rm sig}\epsilon_{\rm sig}(q^2,\cos\theta)g(q^2,\cos\theta) + \frac{1}{N_{\rm CF}} f_{\rm CF}\epsilon_{\rm CF}(q^2,\cos\theta)g(q^2,\cos\theta) \\ & + \frac{1}{N_{\rm IF}} f_{\rm IF}\epsilon_{\rm IF}(q^2,\cos\theta)g(q^2,-\cos\theta) + (1 - f_{\rm sig} - f_{\rm CF} - f_{\rm IF} - f_{K^*hh} - f_{\psi X_s}) \\ & \times \{(f_{K^*\ell h}\mathcal{P}_{K^*\ell h}(q^2,\cos\theta) + (1 - f_{K^*\ell h})\mathcal{P}_{\rm dl}(q^2,\cos\theta)\} + f_{K^*hh}\mathcal{P}_{K^*hh}(q^2,\cos\theta) \\ & + f_{\psi X_s}\mathcal{P}_{\psi X_s}(q^2,\cos\theta). \end{aligned} \tag{3}$$

Here $\mathcal{P}_{K^*\ell h}$, $\mathcal{P}_{\rm dl}$, $\mathcal{P}_{K^*hh}$, and $\mathcal{P}_{\psi X_s}$ are the probability density functions for $K^*\ell h$, dilepton background, K^*hh, and ψX_s, respectively. The quantities $\epsilon_{\rm sig}$ ($N_{\rm sig}$), $\epsilon_{\rm CF}$ ($N_{\rm CF}$), and $\epsilon_{\rm IF}$ ($N_{\rm IF}$) correspond to the efficiency function (normalization) of

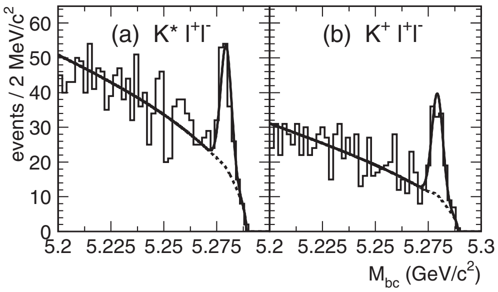

FIG. 1. $M_{\rm bc}$ distributions for (a) $B \to K^* \ell^+ \ell^-$ and (b) $B \to K^+ \ell^+ \ell^-$ samples. The solid and dashed curves are the fit results for the total and background contributions, respectively.

each signal and cross-feed component. Each fraction f is the probability of finding the corresponding component in the data sample for a given $M_{\rm bc}$ value determined from the $M_{\rm bc}$ fit, with the exception of $f_{K^*\ell h}$, which is the fraction of the $K^*\ell h$ events within the background component with misidentification leptons determined from the MC samples. The functions ϵ and $\mathcal{P}$ for the dilepton background, $K^*\ell^\pm h^\mp$, and ψX_s are obtained from MC samples. The $K^* h^+ h^-$ background shape $\mathcal{P}_{K^*hh}$ is obtained from $K^* h^+ h^-$ events and the momentum- and angular-dependent hadron to lepton misidentification probability.

The renormalization scale μ is set to 2.5 GeV as suggested by Ref. [7]. The double differential decay width includes the form factor parameters and the bottom quark mass m_b. We choose the form factor model of Refs. [7,11] and a bottom quark mass of 4.8 GeV$/c^2$.

First, we measure the asymmetry $\tilde{\mathcal{A}}_{\rm FB}$, which is defined as

$$\tilde{\mathcal{A}}_{\rm FB} = \frac{\iint_{-1}^{1} {\rm sgn}(\cos\theta) g(q^2, \theta) d\cos\theta dq^2}{\iint_{-1}^{1} g(q^2, \theta) d\cos\theta dq^2}. \quad (4)$$

We determine the yield in five q^2 bins for $\cos\theta > 0$ and $\cos\theta < 0$ from a fit to the $M_{\rm bc}$ distribution. After efficiency correction for each bin, we obtain

$$\begin{aligned} \tilde{\mathcal{A}}_{\rm FB}(B \to K^*\ell^+\ell^-) &= 0.50 \pm 0.15 \pm 0.02, \\ \tilde{\mathcal{A}}_{\rm FB}(B^+ \to K^+\ell^+\ell^-) &= 0.10 \pm 0.14 \pm 0.01, \end{aligned} \quad (5)$$

where the first error is statistical and the second is systematic. A large asymmetry is measured for $K^*\ell^+\ell^-$ with a significance of 3.4σ. The result for $K^+\ell^+\ell^-$ is consistent with zero as expected.

TABLE I. A_9/A_7 and A_{10}/A_7 fit results for negative and positive A_7 values. The first error is statistical and the second is systematic.

	$A_7 = -0.330$	$A_7 = +0.330$
A_9/A_7	$-15.3^{+3.4}_{-4.8} \pm 1.1$	$-16.3^{+3.7}_{-5.7} \pm 1.4$
A_{10}/A_7	$10.3^{+5.2}_{-3.5} \pm 1.8$	$11.1^{+6.0}_{-3.9} \pm 2.4$

We fit the $K^*\ell^+\ell^-$ candidates with the PDF of Eq. (3). The fit results of ratios of Wilson coefficients are summarized in Table I. Figure 2 shows the fit results projected onto the background-subtracted forward-backward asymmetry distribution in bins of q^2.

We estimate contributions to the systematic error due to uncertainties in the physics parameters, finite q^2 resolution, efficiency, and signal probability. We vary the A_7 value within the range allowed by the branching fraction of $B \to X_s\gamma$ [20]. The bottom quark mass m_b is varied by ± 0.2 GeV$/c^2$. The systematic uncertainty associated with the choice of the form factor model is taken from the deviation in fit results when a model of Ref. [21] is used. The effect of q^2 resolution is estimated using a toy MC study. The effect due to $\cos\theta$ resolution is found to be negligible. The uncertainty in the efficiency is estimated by changing the efficiency for pions with $p < 0.3$ GeV$/c$, electrons with $p < 0.7$ GeV$/c$, and muons with $p < 1$ GeV$/c$ by 10%, 5%, and 10%, respectively, to obtain revised efficiency functions for signal and background PDFs. We change the shape parameters for the signal or background probability functions f and take the difference as an uncertainty in the signal fraction. The parameters are modified by $\pm 1\sigma$ for signal, dilepton background, and $K^* h^+ h^-$. We vary the normalization for cross-feed events and ψX_s by 100% since we cannot determine these background from data. To assign the systematic error due to the uncertainty in the fraction of $K^*\ell^\pm h^\mp$, we change the value of $f_{K^*\ell h}$ by 20%, which corresponds to the difference between the MC sample and sideband events. Table II summarizes the contributions to the systematic error.

The fit results are consistent with the SM values $A_9/A_7 = -12.3$ and $A_{10}/A_7 = 12.8$. In Fig. 3, we show

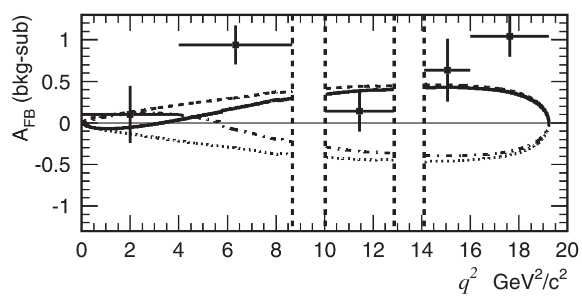

FIG. 2. Fit result for the negative A_7 solution (solid line) projected onto the background-subtracted forward-backward asymmetry and forward-backward asymmetry curves for several input parameters, including the effects of efficiency: A_7 positive case ($A_7 = 0.330$, $A_9 = 4.07$, $A_{10} = -4.21$) (dashed line), A_{10} positive case ($A_7 = -0.280$, $A_9 = 2.42$, $A_{10} = 1.32$) (dotted-dashed line), and both A_7 and A_{10} positive cases ($A_7 = 0.280$, $A_9 = 2.22$, $A_{10} = 3.82$) (dotted line) [9]. The new physics scenarios shown by the dotted-dashed and dotted curves are excluded. The blank regions are excluded by the ψX_s veto.

TABLE II. Summary of systematic errors.

	$A_7 = -0.330$		$A_7 = +0.330$	
Source	A_9/A_7	A_{10}/A_7	A_9/A_7	A_{10}/A_7
A_7 [20]	$+0.2 - 0.0$	± 0.0	$+0.1 - 0.2$	$+0.3 - 0.1$
m_b (4.8 ± 0.2 GeV$/c^2$)	± 0.7	± 0.5	± 0.6	± 0.4
Model dependence	± 0.7	± 1.7	± 1.0	± 2.2
q^2 resolution	± 0.3	± 0.4	± 0.3	± 0.4
Efficiency	± 0.1	± 0.0	± 0.1	± 0.1
Signal probability	$+0.4 - 0.5$	$+0.2 - 0.3$	$+0.4 - 0.5$	± 0.4
Total	± 1.1	± 1.8	$+1.3 - 1.4$	$+2.4 - 2.3$

confidence level (C.L.) contours in the $(A_9/A_7, A_{10}/A_7)$ plane based on the fit likelihood smeared by the systematic error, which is assumed to have a Gaussian distribution. We also calculate an interval in A_9A_{10}/A_7^2 at the 95% C.L. for the allowed A_7 region,

$$-14.0 \times 10^2 < A_9A_{10}/A_7^2 < -26.4. \qquad (6)$$

From this, the sign of A_9A_{10} must be negative, and the solutions in quadrants I and III in Fig. 3 are excluded at the 98.2% confidence level. Since solutions in both quadrants II and IV are allowed, we cannot determine the sign of A_7A_{10}. Figure 2 shows the comparison between the fit results for the negative A_7 value projected onto the forward-backward asymmetry and the forward-backward asymmetry distributions for several input parameters. We exclude the new physics scenarios shown by the dotted and dotted-dashed curves, which have a positive A_9A_{10} value.

In summary, we have measured the ratios of Wilson coefficients in $B \to K^*\ell^+\ell^-$ decay for the first time by studying the forward-backward asymmetry in the angular distribution of leptons. We find evidence for a large forward-backward asymmetry with a significance of 3.4σ. The fit results are consistent with the SM prediction and also with the case where the sign of A_7A_{10} is flipped. We exclude new physics scenarios with positive A_9A_{10} at 98.2% confidence.

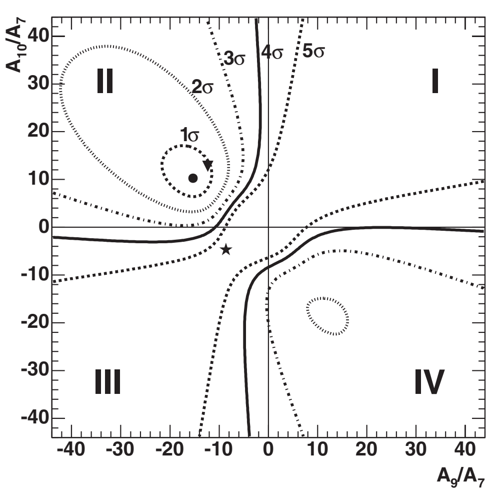

FIG. 3. C.L. contours for negative A_7. Curves show 1σ–5σ contours. The symbols show the fit (circle), SM (triangle), and A_{10}-positive (star) [9] cases. The A_{10}-positive case appears as the dotted-dashed curve of Fig. 2.

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