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First Measurement of the τ Lepton Polarization in the Decay $\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$ at Belle

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The decay $\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau}$ is sensitive to new physics with a non-universal coupling over the three generation of the leptonic sector. We report the first measurement of the τ lepton polarization $P_{\tau}(D^{*})$ and a new measurement of the ratio of the branching fractions $R(D^{*}) = BF(\bar{B} \to D^{*}\tau^{-}\bar{\nu}_{\tau})/BF(\bar{B} \to D^{*}\ell^{-}\bar{\nu}_{\ell})$, where ℓ^{-} denotes e^{-} or μ^{-}, using the full data sample containing $(7.72 \pm 0.11) \times 10^{8}$ $B\bar{B}$ pairs accumulated at the Belle experiment. We reconstruct signal events from $\tau^{-} \to \pi^{-}\nu_{\tau}$ and $\rho^{-}\nu_{\tau}$. Our measurement results in $P_{\tau}(D^{*}) = -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.})$ and $R(D^{*}) = 0.270 \pm 0.035(\text{stat.})^{+0.028}_{-0.025}(\text{syst.})$. These are compatible with the SM prediction within 0.4σ.

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1. Introduction

The decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ is a semileptonic B meson decay with a τ lepton in the final state (semitaounic decay), which in the Standard Model (SM) is mediated by a virtual W boson. If there exists an unknown charged boson appearing in a new physics (NP) model beyond the SM and having an enhanced coupling to the τ lepton, the branching fraction and the decay kinematics may be modified [1]. The modification violates the lepton universality, which is tested by the ratio of the branching fractions $R(D^*) = BF(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)/BF(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)$, where $BF(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)$ is the average of the modes with $\ell^- = e^-$ or μ^-. The SM predicts $R(D^*) = 0.252 \pm 0.003$ [2]. The value significantly smaller than 1 is because the large mass of the τ lepton suppresses the phase space. Experimentally, $R(D^*)$ has been studied by Belle [4], BaBar [5] and LHCb [6]. As of summer 2015, the world average estimated by the heavy flavor averaging group is $R(D^*) = 0.316 \pm 0.016(\text{stat.}) \pm 0.010(\text{syst.})$, which deviates from the SM prediction by 3.3σ [7].

The longitudinal polarization of the τ lepton is defined by $P_\tau(D^*) = (\Gamma^+ - \Gamma^-)/(\Gamma^+ + \Gamma^-)$, where $\Gamma^{+(-)}$ is the decay rate for the τ lepton with a positive (negative) helicity state defined in the rest frame of the leptonic system $\tau^- - \bar{\nu}_\tau$. It is predicted to be -0.497 ± 0.013 in the SM [3], and the value may be modified by the SM; especially it is sensitive to the scalar- and the tensor-type NP currents. While many theoretical works, for example the report in Ref. [3], suggest possible modifications in $P_\tau(D^*)$ due to NP, the polarization $P_\tau(D^*)$ has not been experimentally measured yet.

Using the full data sample of the Belle experiment, containing $(7.72 \pm 0.11) \times 10^8$ $B\bar{B}$ pairs, we conduct a new measurement of $R(D^*)$ statistically independent of the previous result [4] and the first measurement of $P_\tau(D^*)$, reconstructing signal events from $\tau^- \to \pi^- \nu_\tau$ and $\rho^- \nu_\tau$. The data sample has been collected with the Belle detector [8] at the asymmetric-beam-energy e^+e^- collider KEKB [9]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [8].

2. Signal Reconstruction and Extraction

A $B\bar{B}$ pair is produced through the $\Upsilon(4S) \to B\bar{B}$ process. One of the B mesons (referred to as B_{tag}) is first identified from one out of the 1104 decay chains that we consider. A multi-variate analysis method based on the NeuroBayes neural network package is employed to increase the B_{tag} reconstruction efficiency. After one B_{tag} candidate is selected, the signal-side B meson (B_{sig}) is reconstructed by combining a D^* and a charged particle. The D^* is reconstructed from combination of 15 D channels and four D^* modes. The charged particle must satisfy the requirements to be $\pi^\pm$, $\rho^\pm \to \pi^\pm \pi^0$ (for the signal mode $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$) $e^\pm$ or $\mu^\pm$ (for the normalization mode $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$). Events with no additional charged particles nor π^0 candidates except for a B_{tag} and a B_{sig} are selected.

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The yield of the signal mode is extracted using the variable $E_{\rm ECL}$, which is the linearly-summed energy of ECL clusters not used in the event reconstruction. Signal events have values of $E_{\rm ECL}$ consisntent with 0 while the background events take larger values due to additional photons or unreconstructed π^0. For the normalization mode, $M^2_{\rm miss} = (p_{e^+e^-} - p_{tag} - p_{D^*} - p_\ell)^2$ is used, where p denotes the four-momentum of the e^+e^- beam, $B_{\rm tag}$, D^* and ℓ^-. Since there is only one neutrino in the normalization mode, normalization events populate around $M^2_{\rm miss} = 0$ GeV$^2/c^4$. The ratio $R(D^*)$ is measured using the formula

$$R(D^*) = \frac{\varepsilon_{\rm norm} N_{\rm sig}}{\mathscr{B}_\tau \varepsilon_{\rm sig} N_{\rm norm}}, \tag{2.1}$$

where $\mathscr{B}_\tau$ denotes the branching fraction of $\tau^- \to \pi^- \nu_\tau$ or $\tau^- \to \rho^- \nu_\tau$, and $\varepsilon_{\rm sig}$ and $\varepsilon_{\rm norm}$ ($N_{\rm sig}$ and $N_{\rm norm}$) are the efficiencies (the observed yields) for the signal and the normalization mode, respectively. Further details of the event reconstruction and the signal extraction method are described in Ref. [10]

The τ^- polarization is extracted using the distribution

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1}{2}(1 + \alpha P_\tau \cos\theta_{\rm hel}), \tag{2.2}$$

where Γ denotes the decay rate of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$. The helicity angle, $\theta_{\rm hel}$, is the opening angle between the momentum vector of the $\tau\bar{\nu}_\tau$ system and that of the τ-daughter meson in the rest frame of τ. The parameter α describes the sensitivity to P_τ for each τ-decay mode; it is $\alpha = 1$ for $\tau^- \to \pi^- \nu_\tau$ and $\alpha = 0.45$ for $\tau^- \to \rho^- \nu_\tau$. Although the τ momentum is not fully determined experimentally, $\cos\theta_{\rm hel}$ is measured using the following procedure. First, we measure $\cos\theta_{\tau d} = (2E_\tau E_d - m_\tau^2 c^4 - m_d^2 c^4)/(2|\vec{p}_\tau||\vec{p}_d|c^2)$ (E and $\vec{p}$ being the energy and the three-momentum of the τ lepton or the τ-daughter meson d) in the rest frame of the $\tau^-\bar{\nu}_\tau$ system. Using the Lorentz transformation from the rest frame of the $\tau^-\bar{\nu}_\tau$ system to the rest frame of τ, we obtain the equation $|\vec{p}_d^{\,\tau}|\cos\theta_{\rm hel} = -\gamma|\vec{\beta}|E_d/c + \gamma|\vec{p}_d|\cos\theta_{\tau d}$, where $|\vec{p}_d^{\,\tau}| = (m_\tau^2 - m_d^2)/(2m_\tau)$ is the τ-daughter momentum in the rest frame of τ, and $\gamma = E_\tau/(m_\tau c^2)$ and $|\vec{\beta}| = |\vec{p}_\tau|/E_\tau$. Solving this equation, the value of $\cos\theta_{\rm hel}$ is obtained. We use the formula

$$P_\tau(D^*) = \frac{2}{\alpha}\frac{N_{\rm F} - N_{\rm B}}{N_{\rm F} + N_{\rm B}}, \tag{2.3}$$

where $N_{\rm F(B)}$ denotes the number of signal events in the region $\cos\theta_{\rm hel} > (<)0$.

3. Background Estimation

In this analysis, the main background component originates from hadronic B decays because all of visible final-state particles in the signal mode are hadrons. There are many hadronic B decays that have not been measured yet. Besides, it is also difficult to theoretically predict the branching fractions as these decays arise from the complicated hadronization process in the low-energy QCD. We treat the yields of this component as free parameters in the final fit. In addition to the yield, the $E_{\rm ECL}$ shape must be calibrated as each decay mode has a different shape. Our approach is to reconstruct seven modes $\bar{B} \to D^*\pi^-\pi^-\pi^+$, $D^*\pi^-\pi^-\pi^+\pi^0$, $D^*\pi^-\pi^-\pi^+\pi^0\pi^0$, $D^*\pi^-\pi^0$, $D^*\pi^-\pi^0\pi^0$,

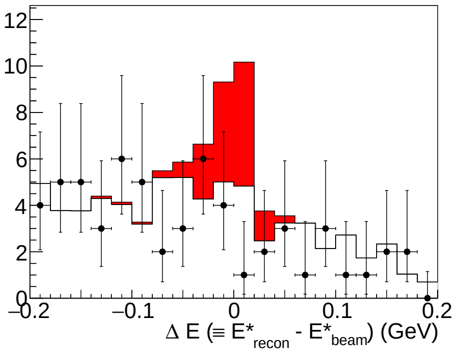

Figure 1: Distribution of $\Delta E (\equiv E^*_B - E^*_{\rm beam})$, where E^*_B and $E^*_{\rm beam}$ are the reconstructed B meson energy and the e^+e^- beam energy, respectively, in the e^+e^- center-of-mass system. The solid histogram shows the MC distribution (with the red and the blank components for the correct B and the fake B candidates, respectively) while the dots are the distribution in the data.

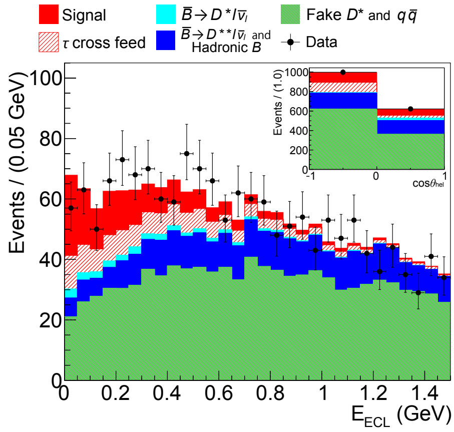

Figure 2: Fit result to the signal sample (all the signal samples are combined). The main panel and the sub panel show the $E_{\rm ECL}$ and the $\cos\theta_{\rm hel}$ distributions, respectively. The red-hatched "τ cross feed" is $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ events reconstructed in a different τ^--daughter sample from the true τ^- decay.

$D^*\pi^-\eta$ and $D^*\pi^-\eta\pi^0$) using the signal-side particles in calibration data samples, and compare the yields between the data and the MC sample. One of the example for the $B^- \to D^{*0}\pi^-\pi^-\pi^+$ channel is shown in Fig. 1. We observe a significant discrepancy between the data and the MC sample, that arises from the overestimation of the branching fraction in our MC simulation. It is corrected by this comparison.

4. Result

From the fit shown in Fig. 2, we obtain the result

$$R(D^*) = 0.270 \pm 0.035(\text{stat.})^{+0.028}_{-0.025}(\text{syst.}),$$
$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat.})^{+0.21}_{-0.16}(\text{syst.}).$$

The systematic uncertainties are estimated as below (where the first and the second values in the parentheses refer to the uncertainties in $R(D^*)$ and $P_\tau(D^*)$, respectively). The main systematic uncertainties arise from the hadronic B decay composition ($^{+7.7}_{-6.9}\%$, $^{+0.13}_{-0.10}$), the statistical fluctuations on the shapes of the probability density functions induced by the limited amount of the MC statistics ($^{+4.0}_{-2.8}\%$, $^{+0.15}_{-0.11}$), the branching fractions and the parameters of the hadronic form factors of the semileptonic B decays ($\pm 3.5\%, \pm 0.05$), the background component containing a falsely-reconstructed D^* candidate ($\pm 3.4\%, \pm 0.02$). In addition, since we fix part of the background yield, we need to consider the uncertainty sources that are common between the signal and the normalization modes: the number of $B\bar{B}$ events, the tagging efficiency, the D branching fractions and the D^* reconstruction efficiency ($\pm 2.3\%, \pm 0.02$). The obtained result is the first measurement of the τ polarization in the semitauonic decay. The result is consistent with the SM prediction.

5. Conclusion

Using hadronic τ decays $\tau^- \to \pi^- \nu_\tau$ and $\rho^- \nu_\tau$, we have measured $P_\tau(D^*)$ and $R(D^*)$. To measure $P_\tau(D^*)$, we have established the method for the $\cos\theta_{\mathrm{hel}}$ measurement without full reconstruction of the four-momentum of the τ lepton. To cope with the background from hadronic B decays, we have calibrated the composition of the decay modes by reconstructing seven B decay channels from the calibration data samples. Our measurement results in $R(D^*) = 0.270 \pm 0.035(\mathrm{stat.})^{+0.028}_{-0.025}(\mathrm{syst.})$ and $P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat.})^{+0.21}_{-0.16}(\mathrm{syst.})$, consistent with the SM prediction. Our study has demonstrated the polarization measurement in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$, that provides an additional dimension in the NP searches with the semitauonic B meson decays.

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