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New results on $R(D)$ and $R(D^*)$ from Belle

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Indications of lepton flavor universality violation in the decays $B \to D^{(*)}\tau\nu$ have triggered substantial interest and could be a hint for new physics. Useful observables to probe new physics in these decays are the ratios of the branching fractions, $R(D^{(*)}) \equiv \mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)$, where $\ell = e$ or μ, and the polarizations of the τ lepton and D^* meson. This article summarizes analyses on those observables in the Belle experiment at the KEKB e^+e^- collider based on the full data set recorded by the Belle detector at the $\Upsilon(4S)$ resonance containing 772 million $B\bar{B}$ pairs. The analyses utilize different methods to reconstruct or tag the accompanying B meson other than the B of the semitauonic decay: semileptonic tagging for the simultaneous measurement of $R(D)$ and $R(D^*)$, and hadronic and inclusive ones for the measurement of the polarizations. In terms of the lepton flavor universality test, the ratio of the branching fractions of the purely leptonic decays, $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)/\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)$, is also interesting because its theoretical uncertainty is small, though the $B^- \to \mu^-\bar{\nu}_\mu$ decay has not been discovered yet. Belle searched for this decay, and the result is also overviewed in this article.

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1. Introduction

The decays[1] $\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau$ are tree-level transitions via the exchange of a virtual W boson in the standard model (SM). Because they contain both a b quark and a τ lepton of the massive third generation, they are interesting in searching for new physics beyond the SM, where the couplings to the fermions are expected to be non-universal among the generations in some models, e.g. Refs. [1, 2]. The ratios of the branching fractions,

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell)}, \qquad (\ell = e \text{ or } \mu), \tag{1.1}$$

are useful observables to probe new physics as they largely cancel out the theoretical uncertainties in the form factors and $|V_{cb}|$ as well as the experimental systematic uncertainties. $R(D)$ and $R(D^*)$ were measured by the BABAR [3] and Belle [4] experiments, and more results on $R(D^*)$ came out from the Belle [5, 6] and LHCb [7, 8] experiments. The world averages of $R(D)$ and $R(D^*)$ exceed the SM predictions by about 3.8σ [9]. That indicates the violation of the lepton flavor universality and could be an intriguing clue to new physics. Other observables which could distinguish the type of new physics are the polarizations of the τ lepton and the D^* meson [10, 11, 12, 13, 14]. Belle is still active in producing new results on the measurements of those observables using the full data set containing 772×10^6 $B\bar{B}$ pairs produced at the KEKB asymmetric-energy e^+e^- collider [15] at the center-of-mass energy $\sqrt{s} = 10.58$ GeV. The ongoing analyses include the simultaneous measurement of $R(D)$ and $R(D^*)$ with semileptonic tagging and the one of the τ and D^* polarizations with inclusive tagging. The overview of these analyses is described in this article. The result of the τ polarization measurement with hadronic tagging [6] is also shown.

The branching fractions of the purely leptonic decays, $\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)$ and $\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)$, and their ratio in terms of the test of the lepton flavor universality are also observables sensitive to new physics. $\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)$ expected in the SM is as small as $(3.80 \pm 0.31) \times 10^{-7}$ [16]. Belle searched for this decay and the result [16] is shown in the last part of this article.

2. Simultaneous measurement of $R(D)$ and $R(D^*)$ with semileptonic tagging

Regarding $R(D)$, there are only two direct measurements with hadronic tagging, and another measurement with an independent data set is awaited. In the previous measurement of $R(D^*)$ with semileptonic tagging, pairs of $B^0\bar{B}^0$ from $\Upsilon(4S)$ both decaying to $D^*\ell$, where $\ell = \tau$ for the signal B and $\ell = e$ or μ for the tag B, were selected to have a high purity. The ongoing analysis also utilizes the semileptonic tagging with additional decay channels including one or two D mesons instead of D^*, namely $B^0\bar{B}^0 \to (D^{(*)-}\ell^+)(D^{(*)+}\ell^-)$, and also $B^+B^- \to (\bar{D}^{(*)0}\ell^+)(D^{(*)0}\ell^-)$. It is done with the Belle II software framework [17], and a multivariate analysis with a boosted-decision-tree classifier is adopted to acquire a high reconstruction efficiency. The result will come out soon.

3. Measurement of the τ and D^* polarizations in $\bar{B} \to D^*\tau\bar{\nu}$

The polarization of the τ lepton, $P_\tau(D^*)$, was measured in the hadronic two-body decays, $\tau^- \to h^-\nu_\tau$ ($h = \pi$ or ρ), where the angular distribution of the daughter meson in the τ rest frame

[1] Charge-conjugate decays are implied throughout this article.

is described as

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{hel}}} = \frac{1}{2}\left[1+\alpha P_\tau(D^*)\cos\theta_{\mathrm{hel}}\right], \qquad \alpha = \begin{cases} 1 & (\tau^- \to \pi^- \nu_\tau), \\ \dfrac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2} & (\tau^- \to \rho^- \nu_\tau). \end{cases} \tag{3.1}$$

Here, Γ is the total decay rate, θ_{hel} is the angle between the meson momentum and the opposite direction of the momentum of the virtual W boson from the B meson decay, and m_τ and m_ρ are the masses of the τ lepton and ρ meson, respectively. The polarization of the ρ vector meson was not measured, and hence Eq. (3.1) was obtained by just averaging the angular distributions of the transverse and longitudinal polarizations of the ρ meson [18]. θ_{hel} was practically measured in the rest frame of the virtual W boson from B as $\theta_{\tau h}$, the half apex angle of the cone of which axis is $\vec{p}_h$, or the momentum of the τ-daughter meson h. The τ momentum, $\vec{p}_\tau$, can be constrained to lie on this cone, and $\theta_{\tau h}$ is measured as $\cos\theta_{\tau h} = (2E_\tau E_h - m_\tau^2 - m_h^2)/(2|\vec{p}_\tau||\vec{p}_h|)$, where E_τ is the energy of the τ lepton, and E_h and m_h are the energy and mass of the daughter meson, respectively. A boost in an arbitrary direction on the cone from the W to τ rest frames translates $\cos\theta_{\tau h}$ to $\cos\theta_{\mathrm{hel}}$. $|\vec{p}_\tau|$ in the W rest frame depends only on the momentum transfer, which can be reconstructed from the four-momenta of the B and D^* mesons. Hence the accompanying B meson and the D meson from the D^* decay were reconstructed only from the hadronic decays. $P_\tau(D^*)$ was deduced from the asymmetry of the signal yield in the forward ($\cos\theta_{\mathrm{hel}} > 0$) and the backward ($\cos\theta_{\mathrm{hel}} < 0$) regions. The result was $P_\tau(D^*) = -0.38 \pm 0.51(\mathrm{stat})^{+0.21}_{-0.16}(\mathrm{syst})$.

The measurements of the τ and D^* polarizations with inclusive tagging are ongoing. In the inclusive tagging, candidates for daughters of the signal B meson are selected, and then the accompanying B meson is reconstructed inclusively from all the remaining particles [19, 20]. This tagging method has a higher efficiency than the others but suffers from larger background. The D^* polarization is measured from the angular distribution of the D^* decay,

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{hel}}} = \frac{3}{4}\left[2F_L^{D^*}\cos^2\theta_{\mathrm{hel}} + F_T^{D^*}\sin^2\theta_{\mathrm{hel}}\right], \tag{3.2}$$

where $F_{L(T)}^{D^*}$ is the fraction of the longitudinal (transverse) D^* polarization ($F_L^{D^*} + F_T^{D^*} = 1$) and θ_{hel} is the angle between the direction of the D meson and the one opposite the B meson in the D^* rest frame. Compared with the measurement of the τ polarization, the one of the D^* polarization has an advantage of not being affected by the τ decays, which are hard to reconstruct. On the other hand, a strong dependence of the acceptance on $\cos\theta_{\mathrm{hel}}$ and the momentum transfer has to be properly treated. The result is expected to be published soon.

4. Search for $B^- \to \mu^- \bar{\nu}_\mu$ decays

The branching fraction of the purely leptonic decays in the SM is

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B, \tag{4.1}$$

where G_F is the Fermi constant, m_ℓ is the mass of the charged lepton, m_B, f_B and τ_B are the mass, decay constant and lifetime of the B meson, respectively, V_{ub} is the CKM matrix element representing the coupling between the u and b quarks, and the neutrino is assumed to be massless. Once

$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)$ is measured precisely, the ratio of the branching fractions, $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)/\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)$, where G_F, f_B, V_{ub} and τ_B cancel out, would be a powerful probe for new physics as it can be predicted very precisely in the SM.

The $B^- \to \mu^- \bar{\nu}_\mu$ decays were searched for by the untagged method, where a well-reconstructed muon candidate of the decay was selected and then the rest of the event was required to resemble the accompanying B^+ meson. This B^+ meson should have the invariant mass close to the nominal m_B and the total energy close to the nominal B meson energy. The momentum of the muon from the two-body B^- decay without radiation is monochromatic in the B meson rest frame, and the one in the $\Upsilon(4S)$ center-of-mass frame, p^*_μ, is smeared to the range (2.476, 2.812) GeV/c by the boost of the B meson. The signal yield was extracted by a binned maximum-likelihood fit in the p^*_μ-o_{nn} plane, where o_{nn} is a neural network output variable to separate the signal from backgrounds. A 2.4σ excess of the signal yield was found above background including systematic uncertainties. It corresponds to $\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu) = (6.46 \pm 2.22(\text{stat}) \pm 1.60(\text{syst})) \times 10^{-7}$ or $[2.9, 10.7] \times 10^{-7}$ for a frequentist 90% confidence interval.

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