B → ℓν - Belle results and outlook for Belle II

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1 Introduction

The leptonic decays \( B^− \rightarrow ℓ^−\nu_ℓ \) \( (ℓ = e, \mu, \tau) \) provide opportunities for testing the Standard Model (SM) and for searching for new physics\[1\]. In the SM, the branching ratio \( \mathcal{B}(B^− \rightarrow ℓ^−\nu_ℓ) \) is proportional to \( f_B^2|V_{ub}|^2 \), where \( f_B \) is the \( B \) meson decay constant and \( V_{ub} \) is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element \[1\]. The expected branching ratios in the SM are \( O(10^{-4}) \), \( O(10^{-7}) \), and \( O(10^{-11}) \) for \( ℓ = \tau, \mu, e \), respectively, where the mass difference between \( \tau, \mu, \) and \( e \) affects the values.

Physics beyond the SM could suppress or enhance \( \mathcal{B}(B^− \rightarrow ℓ^−\nu_ℓ) \) via exchange of a new charged particle such as a charged Higgs boson \[2, 3, 4\]. In this report, the results obtained at the Belle experiment are introduced. An outlook for the Belle II experiment is also shown.

2 Belle results

The leptonic decays \( B^− \rightarrow ℓ^−\nu_ℓ \) include neutrinos in the final state, which cannot be detected by the Belle detector. At the Belle experiment, it is exploited that a \( B \) meson pair is generated from the process \( e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB \). We reconstruct one of the \( B \) mesons ("B_{tag}") and identify the signal decays in the other \( B \) mesons ("B_{sig}").

The first evidence of \( B^− \rightarrow \tau^−\nu_τ \) was reported by the Belle collaboration with a significance of 3.5 standard deviations (\( σ \)) and a measured branching ratio of \( \mathcal{B}(B^− \rightarrow \tau^−\nu_τ) = [1.79^{+0.56}_{-0.49}(\text{stat})^{+0.46}_{-0.51}(\text{syst})] \times 10^{-4} \) \[5\]. This measurement used hadronic modes for reconstructing \( B_{tag} \) ("hadronic tag") and a data sample corresponding to \( 449 \times 10^6 \) \( BB \) events. This was followed by a measurement of \( \mathcal{B}(B^− \rightarrow \tau^−\nu_τ) = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4} \) with a significance of 3.6\( σ \) (Fig. 1(a)) \[6\]. This measurement used semileptonic modes for reconstructing \( B_{tag} \) ("semileptonic tag") and a data sample corresponding to \( 657 \times 10^6 \) \( BB \) events.

In the summer of 2012, the Belle collaboration updated the result for the hadronic tag using Belle’s final data sample corresponding to \( 772 \times 10^6 \) \( BB \) events \[7\]. The

\[1\] Charge-conjugate decays are implied throughout this report unless otherwise stated.
branching ratio is obtained to be $\mathcal{B}(B^-\rightarrow \tau^{-}\nu_{\tau}) = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$ with a significance of 3.0σ (Fig. 1(b) and (c)). By employing a neural network-based method for the hadronic tag and a two-dimensional fit for the signal extraction, along with a larger data sample, both statistical and systematic precisions are significantly improved. Combined with the measurement based on the semileptonic tag [6] taking into account all the correlated systematic errors, the branching ratio is found to be $\mathcal{B}(B^-\rightarrow \tau^{-}\nu_{\tau}) = (0.96 \pm 0.26) \times 10^{-4}$ with a significance of 4.0σ. The result is consistent with the value $(0.72^{+0.12}_{-0.08}) \times 10^{-4}$ obtained from a global fit to CKM matrix elements assuming the SM (Fig. 2(a)) [8]. Using our new combined result and parameters found in Ref. [9], we obtain $f_B|V_{ub}| = [7.4 \pm 0.8(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-4}$ GeV. Our result also provides constraints on new physics models including charged Higgs bosons (Fig. 2(b)).

For the $B^- \rightarrow \mu^{-}\nu_{\mu}$ and $B^- \rightarrow e^{-}\nu_{e}$ decays, significant signal has not been obtained. The Belle collaboration obtained the upper limits of $\mathcal{B}(B^-\rightarrow \mu^{-}\nu_{\mu}) < 1.7 \times 10^{-6}$ and $\mathcal{B}(B^-\rightarrow e^{-}\nu_{e}) < 9.8 \times 10^{-7}$ at 90% confidence level (C.L.) by reconstructing $B_{\text{tag}}$ using all the remaining particles after removing $\mu^{-}$ and $e^{-}$ in the $B_{\text{sig}}$ reconstruction (“inclusive tag”) [11]. This measurement used a data sample corresponding to $657 \times 10^6 B\bar{B}$ events. In the summer of 2012, the Belle collaboration also obtained the upper limits of $\mathcal{B}(B^-\rightarrow \mu^{-}\nu_{\mu}) < 2.5 \times 10^{-6}$ and $\mathcal{B}(B^-\rightarrow e^{-}\nu_{e}) < 3.5 \times 10^{-6}$ at 90% C.L. using the hadronic tag and the full data sample [12]. The results are consistent with the SM expectations.

![Figure 1: Signal extraction for $B^- \rightarrow \tau^{-}\nu_{\tau}$ at the Belle experiment. The solid circles with error bars are data. The solid histograms show the fit results. The dashed histograms in (b) and (c) show the signal component, while the hatched histogram in (a) and the dotted histograms in (b) and (c) show the background component.](image-url)
(a) Comparison for $B(B^- \to \tau^- \nu_{\tau})$ between the direct measurement, the Belle result as well as a world average $B(B^- \to \tau^- \nu_{\tau}) = (1.15 \pm 0.23) \times 10^{-4}$, and a SM estimate from the CKM global fit [8].

(b) Constraint on $\tan \beta$ and the charged Higgs mass in the type II two Higgs doublet model [2]. The filled regions indicate excluded regions at 95% C.L. The factors $f_B = (190 \pm 9)$ MeV [10] and $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ [9] are used.

**Figure 2:** A comparison of the $B(B^- \to \tau^- \nu_{\tau})$ result with a SM estimate and a constraint on the type II two Higgs doublet model. We use the Belle’s combined result of $B(B^- \to \tau^- \nu_{\tau}) = (0.96 \pm 0.26) \times 10^{-4}$.

## 3 Outlook for Belle II

The KEKB collider and the Belle detector will be upgraded to the SuperKEKB collider and the Belle II detector, respectively [13]. The design center-of-mass energy for SuperKEKB is on the $\Upsilon(4S)$ resonance, which is the same as KEKB. The design luminosity for SuperKEKB is $8.0 \times 10^{35}$ cm$^{-2}$s$^{-1}$, which is about 40 times larger than the current world record of $2.1 \times 10^{34}$ cm$^{-2}$s$^{-1}$ achieved by KEKB. The target integrated luminosity is 50 ab$^{-1}$, which is about 50 times larger than KEKB. The Belle II detector is designed to cope with higher background, which is estimated by extrapolating the results of the operations of KEKB and Belle. The Belle II detector has better performance than the Belle detector in the vertex determination based on the pixel detectors and the particle identification based on the imaging Cherenkov detectors. The physics run is planned to start in 2016.

The measurements of $B(B^- \to \ell^- \nu_{\ell})$ are one of the most important physics programs at the Belle II experiment. A key experimental issue is to understand the extra energy distribution (see Fig. 1 (a) and (b)), which is a main variable for discriminating the signal from the background, over the higher beam background level. It is also important to improve the theoretical understanding of $f_B$ and the precision of $|V_{ub}|$ determination from the $b \to u$ transitions so that we can use $B(B^- \to \ell^- \nu_{\ell})$ for a
test of SM and new physics.

For $\mathcal{B}(B^- \to \tau^- \nu_{\tau})$, we expect a precision of about 10% and a few % at the integrated luminosity of 5 ab$^{-1}$ and 50 ab$^{-1}$, respectively. For this measurement, we need to estimate the systematic uncertainties with better precision. The main systematic uncertainties were estimated by using the data sample at the Belle experiment, and a meaningful improvement is expected using increased data sample at the Belle II experiment. Fig. 3 shows the expectations for the constraint on the type II two Higgs doublet model [2] and the 2-parameter nonuniversal Higgs model with a Higgs boson mass of 125 GeV [4]. Stringent constraints on these models are expected to be obtained. For $\mathcal{B}(B^- \to \mu^- \nu_{\mu})$, we expect a 5$\sigma$ observation at an integrated luminosity of 5 ab$^{-1}$ assuming the SM branching ratio. For both $\mathcal{B}(B^- \to \mu^- \nu_{\mu})$ and $\mathcal{B}(B^- \to e^- \nu_e)$, we expect a sensitivity of $O(10^{-8})$ at an integrated luminosity of 50 ab$^{-1}$. These measurements will provide important insight into lepton universality.

(a) Constraint on $\tan \beta$ and the charged Higgs mass in the type II two Higgs doublet model [2]. The filled regions indicate excluded regions at 95% C.L. Assumed central values are $\mathcal{B}(B^- \to \tau^- \nu_{\tau}) = 1 \times 10^{-4}$, $f_B = 190$ MeV, and $|V_{ub}| = 4.15 \times 10^{-3}$. Assumed error for $f_B^2 |V_{ub}|^2$ is relatively 4%.

(b) Constraint on the 2-parameter nonuniversal Higgs model [4]. The blue and orange dots are obtained for allowed parameter regions in $m_0 < 5$ TeV and $m_0 < 20$ TeV, respectively. The black dotted and solid lines show the $\pm 2\sigma$ boundary and the central value, respectively, for the world average of $\mathcal{B}(B^- \to \tau^- \nu_{\tau})$ in 2007. The green region shows an expectation for Belle II.

Figure 3: Expectation for the constraint on new physics models at an integrated luminosity of 50 ab$^{-1}$ at Belle II.
4 Conclusion

The leptonic decays $B^- \rightarrow \ell^- \nu_\ell$ provide opportunities for testing the SM and for searching for new physics. Evidence of signal has been obtained for $B^- \rightarrow \tau^- \nu_\tau$ using hadronic and semileptonic tags at Belle. Upper limits have been obtained for $B^- \rightarrow \mu^- \nu_\mu$ and $B^- \rightarrow e^- \nu_e$ using inclusive and hadronic tags at Belle. All the results are consistent with the SM, and provide constraints on new physics models including charged Higgs bosons. Stringent tests of the SM and new physics will be performed by the measurements with better precision at Belle II.

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