Rare and forbidden B and tau decays in the Belle

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Abstract. A search for the purely leptonic decays \( B^+ \to e^+ \nu_e \) and \( B^+ \to \mu^+ \nu_\mu \) was performed using the 772 million \( B\bar{B} \) pairs collected by the Belle detector at the KEKB asymmetric-energy \( e^+e^- \) collider. There was no evidence of a signal in either decay modes. A heavy neutral lepton-like new particle and heavy neutrino searches were also performed, but no significant signals were observed. Lepton flavor violation in \( \tau \) decays was studied with an almost full data sample and the upper limits obtained were in the order of \( 10^{-8} \). In this paper, recent results that can give any constraints to new physics are briefly described.

1. Introduction
A 710 fb\(^{-1} \) data sample containing 772 million \( B \) meson pairs was collected at a resonance of \( \Upsilon(4S) \) with the Belle detector \[1\] at the KEKB accelerator. The KEKB is an energy asymmetric \( e^+e^- \) (3.5 on 8.0 GeV) collider \[2\] operating at the energy of \( \Upsilon(4S) \). The \( \Upsilon(4S) \) decays exclusively to \( B^0\bar{B}^0 \) or \( B^+B^- \).

The Belle detector is a large-solid-angle magnetic spectrometer consisting of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of silica aerogel threshold cherenkov counters (ACC), time-of-flight scintillation counters (ToF), and a CsI(Tl) crystal electromagnetic calorimeter (ECL). These subdetectors are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. The Belle detector covers \( 4\pi \), and the initial state is well known; therefore, this is perfect environment for studies of \( B \) decays with neutrinos in their final state.

Here, the study results of the leptonic decays, and new particle searches such as lepton-like neutral particle and heavy neutrino which are based on a 710 fb\(^{-1} \) data sample will be described. The lepton flavor violation (LFV) of \( \tau \) decays highly suppressed in the standard model (SM) is studied and the result is also briefly presented.

2. Leptonic decays: \( B^+ \to e^+ \nu_e \) and \( B^+ \to \mu^+ \nu_\mu \)
Purely leptonic decays proceed via annihilation of the charged \( B \) meson’s constituent quarks into a lepton and a neutrino of the same generation. In the SM, this process is mediated by a \( W^+ \) boson leading to a branching fraction \[3\] as follows:

\[
B(B^+ \to l^+ \nu_l) = \frac{G_F^2m_{B^+}m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_{B^+}^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B,
\]

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where $G_F$ is the Fermi coupling constant, $m_l$ is the mass of the charged lepton, $m_B$ is the mass of the $B^+$ meson, $\tau_B$ is the lifetime of the $B^+$ meson, $V_{ub}$ is the element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [4], and $f_B$ is the $B$ decay constant. New physics (NP) contributions might interfere with the SM and modify the expectations. Most prominent is the charged Higgs from the two-Higgs-doublet model [5]; the branching fraction of the $B$ to $l\nu_l$ can be greatly enhanced by as much as $(1-\tan^2\beta m_B^2/m_H^2)^2$. Therefore, this decay can either test the SM or measure the product of the least-well-known parameters, $f_B^2 |V_{ub}|^2$. The expected branching fractions in the SM using the achieved value and world average for each parameter [6][7] are in the order of $10^{-11}$, $10^{-7}$, and $10^{-4}$ for $B^+ \to e^+\nu_e$ (e mode), $B^+ \to \mu^+\nu_\mu$ (µ mode), and $B^+ \to \tau^+\nu_\tau$ (τ mode), respectively. Due to helicity suppression in the SM, e mode and μ mode have relatively small branching fractions. On the other hand, τ mode has a larger branching fraction and has been measured previously by the Belle [8] and BABAR [9] experiments, resulting in the order of $10^{-4}$.

To study the leptonic decays of the $e$ and $\mu$ modes [10], the hadronic tagging method based on a hierarchical neural network [11] is used. The signal events are extracted from the signal lepton’s momentum ($p_B^l$) in the rest frame of the $B_{sig}$. Due to the two-body decay of the signal, we expected the signal events to peak sharply around 2.64 GeV/c, and anticipated a very clean signal with low background. The background in the signal region ($2.6 \text{ GeV/c} < p_B^l < 2.7 \text{ GeV/c}$) was estimated by fitting the sideband of $p_B^l$ and extrapolating it into the signal region. For the peaking background, Monte Carlo (MC) modeling was employed. After all backgrounds were subtracted, the signal event was investigated. In the $p_B^l$ signal region, there were no observed signal events for either search, as shown in Fig. 1. The upper limits at 90% C.L. were set to be $3.4 \times 10^{-6}$ and $2.7 \times 10^{-6}$ for $e$ mode and $\mu$ mode, respectively. These are by far the most stringent limits.

Figure 1. The unbinned maximum likelihood fits of the total background PDF to data for $B^+ \to e^+\nu_e$ (left) and $B^+ \to \mu^+\nu_\mu$ (right). The points with error bars are the experimental data. The dashed and the dotted lines show the background PDF in the sideband and signal regions, respectively. The distributions of the signal MC, displayed as the histogram, are scaled by $10^6$ and 40 times the SM expectation for $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$, respectively.

3. Searching for massive invisible particle
Figure 2 shows a Feynman diagram for $B^+ \to l^+ X$. There is no well-matched theoretical model for $X$ particles; we assumed that massive particles would replace neutrinos in the pure leptonic $B$ decay. The $X$ particle may be a candidate for dark matter or the light neutralino in the supersymmetry (SUSY). We expected the $X$ particle to have no electric charge and to be a spin 1/2 particle. We assumed a range of possible mass for the $X$ particle from 0.1 GeV/c$^2$ to 1.8 GeV/c$^2$ in steps of 100 MeV/c$^2$. 
Figure 2. Feynman diagram of \( B^+ \to l^+ X \).

The method of analysis was similar to \( B^+ \to l^+ \nu_l \) as described in Sect. 2; the systematics were also similar. However, a loose momentum cut and loose impact parameter selection were applied. Depending on the mass of the \( X \) particle, the peak of \( p_T^B \) was changed; therefore, cuts needed to be optimized for each \( X \) mass and different cuts were applied for each \( X \). After all cuts were applied and the background was subtracted, the signal region of \( p_T^B \) is investigated for each \( X \) mass and preliminary upper limits in the branching fractions at 90\% C.L. were obtained to be in the order of \( 10^{-6} \).

4. Search for heavy neutrinos
The masses of particles in the SM are generated by the coupling of the Higgs field to the left- and right-handed components of a given particle. There are no right-handed neutrinos in the SM; rather, neutrinos in the SM are strictly massless. However, experimental data on neutrino oscillations have shown that neutrinos are not massless [6]. Many models beyond the SM suggest various explanations for this, and some models assume a heavy neutrino existence [12].

The direct search for heavy neutrinos in \( B \to Xl\nu_h (\nu_h \to l^\pm \pi^\mp) \) is described in Ref. [13]. The mass range to search for a heavy neutrino is \( 0.5 \text{ GeV}/c^2 \leq M(\nu_h) \leq 5.0 \text{ GeV}/c^2 \) and approach is divided depending on the mass as follows.

- \( M(\nu_h) < 2.0 \text{ GeV}/c^2 \): look for \( X = D \) or \( D^* \) using recoil mass,
- \( M(\nu_h) \geq 2.0 \text{ GeV}/c^2 \): look for \( X = D^{(*)}, \) light meson and nothing.

Various backgrounds were suppressed by using the number of tracks requirement, strict lepton identification, vertex quality, distance of the lepton-pion vertex, and the distance between the closest associated hit in the SVD/CDC to the vertex of \( \nu_h \). By using the number of neutrinos detected, the upper limit of the branching fraction for \( \nu_{\nu_l} \) mixing was obtained and the results are shown along with other experimental results in Fig. 3. The corresponding upper limit for the product branching fraction for heavy neutrino mass (2.0 GeV/c^2) was in the order of \( 10^{-7} \).

Figure 3. Comparison of the obtained upper limits for \( |U_e|^2 \) (left) and \( |U_\mu|^2 \) (right) with the existing experimental results.

5. Lepton flavor violation in tau decays
LFV in charged lepton decays is forbidden in the SM, or is highly suppressed even if neutrino mixing is taken into account. On the other hand, the extension of the SM and many other new models predict LFV with branching fractions as large as \( 10^{-8} \) [14]. Moreover, \( \tau \) lepton is a good
tool when it comes to searching for the LFV decays due to enhanced coupling to the NP, as well as the large number of LFV decay modes. In the study result of the LFV in $\tau \rightarrow l hh$, $l$ is the electron or muon and $h$ is the charged pion or kaon, as described in Ref. [15].

An 854 fb$^{-1}$ data sample collected at or below resonances of $\Upsilon(4S)$ and $\Upsilon(5S)$ was used and a total of 14 modes were investigated. Blind analysis was performed by searching the signal events on the $\tau$ mass-$\Delta E$ plane, and the tagging method was used. $\tau_{\text{tag}}$ and $\tau_{\text{sig}}$ were required to be 1 prong decay and LFV final state, respectively. For background suppression, various observables were used, for example, an opening angle between the missing momentum and charged track on the tag side, thrust $T$, and missing mass ($m_{\text{miss}}^2$). To evaluate the branching fraction, elliptical signal regions that contain $\pm 3\sigma$ of the signal MC satisfying all selection criteria were used for each decay mode. As a result, one event was found for $\tau \rightarrow \mu \pi h$. For the other 12 modes, no events were observed in the signal regions. The number of observed signal events for all modes agreed with number of expected background events. The upper limits at 90% C.L. were obtained as $(2.0 \sim 8.6) \times 10^{-8}$, representing an improved on previously published upper limits [16] by a factor of about 1.8 on average.

6. Summary

Most stringent upper limits at 90% C.L. on $B^+ \rightarrow e^+(\mu^+)\nu$ have been obtained as $3.4(2.7) \times 10^{-6}$. The search for a heavy neutral lepton-like new particle was performed with $B^+ \rightarrow l^+ X$, where $X$ can be any invisible fermion particle, and preliminary results in the upper limits were in the order of $10^{-6}$ for 0.1 GeV/$c^2 < M_X < 1.8$ GeV/$c^2$. A heavy neutrino search was also performed and the upper limit on mixing of $\nu_l - \nu_\tau$ was set in the mass range of $0.5 \text{ GeV}/c^2 \sim 5.0 \text{ GeV}/c^2$. Up to now, there have been no clues concerning NP contribution from leptonic $B$ decays. We studied 48 different LFV modes in $\tau$ decays, 46 of which were analyzed with an almost full data sample and the upper limits obtained on the branching fractions were in the order of $10^{-8}$. In particular, the upper limits that were improved by a factor of about 1.8 on average were obtained for $\tau \rightarrow l^+ hh'$.

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