Measurement of $B^- \rightarrow \tau^- \bar{\nu}_\tau$ Decay With a Semileptonic Tagging Method

I. Adachi, T. A. Aziz, S. Bahinipati, K. Arinstein, T. Aso, V. Aulchenko, T. Aushev, T. Aziz, S. Bahinipati, A. M. Bakich, V. Balagura, Y. Ban, E. Barberio, A. Bay, I. Bedny, K. Belous, V. Bhardwaj, U. Bitenc, S. Blyth, A. Bondar, A. Bozek, M. Bracko, T. Brodzicka, T. E. Browder, M.-C. Chang, P. Chang, Y.-W. Chang, Y. Chao, A. Chen, K.-F. Chen, B. G. Cheon, C.-C. Chiang, R. Chistov, I.-S. Cho, S.-K. Choi, Y. Choi, Y. K. Choi, S. Cole, J. Dalseno, M. Danilov, A. Das, M. Dash, A. Drutskoy, W. Dungel, S. Eidelman, D. Epifanov, S. Esen, S. Fratina, H. Fujii, M. Fujikawa, N. Gabyshov, A. Garmash, P. Goldenzweig, B. Golob, M. Grosse Perdekamp, H. Guler, H. Guo, J. Haba, K. Hara, Y. Hasegawa, N. C. Hastings, K. Hayasaka, H. Hayashii, M. Hazumi, D. Heffernan, T. Higuchi, H. Hödlmoser, T. Hokue, Y. Horii, K. Hoshina, W.-S. Hou, Y. B. Hsiung, H. J. Hyun, T. Iijima, K. Ikado, K. Inami, A. Ishikawa, H. Ishino, R. Itoh, M. Iwabuchi, M. Iwasaki, Y. Iwasaki, C. Jacoby, N. J. Joshi, M. Kaga, D. H. Kah, H. Kakudo, H. Kakuno, J. H. Kang, P. Kapusta, S. U. Kataoka, N. Katayama, H. Kawai, T. Kawasuki, A. Kibayashi, H. Kichimi, H. J. Kim, H. O. Kim, J. H. Kim, S. K. Kim, Y. I. Kim, Y. J. Kim, K. Kinoshita, S. Korpar, Y. Kozakai, P. Križan, P. Krokovny, R. Kumar, E. Kurihara, Y. Kuroki, A. Kuzmin, Y.-J. Kwon, S.-H. Kyeong, J. S. Lange, G. Leder, J. Lee, J. S. Lee, S. E. Lee, T. Lesiak, J. Li, A. Limosani, S.-W. Lin, C. Liu, D. Liu, D. Liventsev, J. MacNaughton, F. Mandl, D. Marlow, T. Matsumura, A. Matyja, S. McOnie, T. Medvedeva, Y. Mikami, K. Miyabayashi, H. Miyata, Y. Miyazaki, R. Mizuk, G. R. Moloney, T. Mori, T. Nagamine, Y. Nagasaka, Y. Nakahama, I. Nakamura, E. Nakano, M. Nakao, H. Nakayama, H. Nakazawa, Z. Natkaniec, K. Neichi, S. Nishida, K. Nishimura, Y. Nishio, I. Nishizawa, O. Nitoh, S. Noguchi, T. Nozaki, A. Ogawa, S. Ogawa, T. Ohshima, S. Okuno, S. L. Olsen, S. Ono, W. Ostrowicz, H. Ozaki, P. Pakhlov, G. Pakhlova, H. Palka, C. W. Park, H. Park, K. S. Park, N. Parslow, L. S. Peak, M. Pernicka, R. Pestonjuk, M. Peters, L. E. Piilonen, A. Poluektov, J. Rorie, M. Rozanska, H. Sahoo, Y. Sakai, N. Sasao, K. Sayeed, T. Schietinger, O. Schneider, P. Schönmeier, J. Schümann, C. Schwanda, A. J. Schwartz, R. Seidl, A. Sekiya, K. Senyo, M. E. Sevior, L. Shang, M. Shapkin, V. Shebalin, C. P. Shen, H. Shibuya, S. Shinomiya, J.-G. Shiu, B. Shwartz, V. Sidorov, J. B. Singh, A. Sokolov, A. Somov, S. Stanić, M. Starić, J. Stypula, A. Sugiyama, K. Sumisawa, T. Sumiyoshi, S. Suzuki, S. Y. Suzuki, O. Tajima, F. Takasaki, K. Tamai, N. Tamura, M. Tanaka, N. Taniguchi, G. N. Taylor, Y. Teramoto, I. Tikhomirov, K. Trabelsi, Y. F. Tse, T. Tsuboyama, Y. Uchida, S. Uehara, Y. Ueki, K. Ueno, T. Uglov, Y. Unno, S. Uno, P. Urquijo, Y. Ushiroda, Y. Uso, G. Varner.
K. E. Varvell, K. Vervink, S. Villa, A. Vinokurova, C. C. Wang, C. H. Wang, J. Wang, M.-Z. Wang, P. Wang, X. L. Wang, M. Watanabe, Y. Watanabe, R. Wedd, J.-T. Wei, J. Wicht, L. Widhalm, J. Wiechczynski, E. Won, B. D. Yabsley, A. Yamaguchi, H. Yamamoto, M. Yamaoka, Y. Yamashita, M. Yamauchi, C. Z. Yuan, Y. Yusa, C. C. Zhang, L. M. Zhang, Z. P. Zhang, V. Zhilich, V. Zhulanov, T. Zivko, A. Zupane, N. Zwahlen, and O. Zyukova

(The Belle Collaboration)

1Budker Institute of Nuclear Physics, Novosibirsk
2Chiba University, Chiba
3University of Cincinnati, Cincinnati, Ohio 45221
4Department of Physics, Fu Jen Catholic University, Taipei
5Justus-Liebig-Universität Gießen, Gießen
6The Graduate University for Advanced Studies, Hayama
7Gyeongsang National University, Chinju
8Hanyang University, Seoul
9University of Hawaii, Honolulu, Hawaii 96822
10High Energy Accelerator Research Organization (KEK), Tsukuba
11Hiroshima Institute of Technology, Hiroshima
12University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
13Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
14Institute of High Energy Physics, Vienna
15Institute of High Energy Physics, Protvino
16Institute for Theoretical and Experimental Physics, Moscow
17J. Stefan Institute, Ljubljana
18Kanagawa University, Yokohama
19Korea University, Seoul
20Kyoto University, Kyoto
21Kyungpook National University, Taegu
22École Polytechnique Fédérale de Lausanne (EPFL), Lausanne
23Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana
24University of Maribor, Maribor
25University of Melbourne, School of Physics, Victoria 3010
26Nagoya University, Nagoya
27Nara Women’s University, Nara
28National Central University, Chung-li
29National United University, Miao Li
30Department of Physics, National Taiwan University, Taipei
31H. Niewodniczanski Institute of Nuclear Physics, Krakow
32Nippon Dental University, Niigata
33Niigata University, Niigata
34University of Nova Gorica, Nova Gorica
35Osaka City University, Osaka
36Osaka University, Osaka
37Panjab University, Chandigarh
38Peking University, Beijing
Abstract

We present a new measurement of the decay $B^- \rightarrow \tau^- \bar{\nu}_\tau$ with a semileptonic $B$ tagging method, using a data sample containing $657 \times 10^6 B \bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider. A sample of $B \bar{B}$ pairs are tagged by reconstructing one $B$ meson decaying semileptonically. We detect the $B^- \rightarrow \tau^- \bar{\nu}_\tau$ candidate in the recoil. We obtain a signal with a significance of 3.8 standard deviations including systematics, and measure the branching fraction to be $B(B^- \rightarrow \tau^- \bar{\nu}_\tau) = (1.65^{+0.38}_{-0.37}(\text{stat})^{+0.35}_{-0.37}(\text{syst})) \times 10^{-4}$. This result confirms the evidence for $B^- \rightarrow \tau^- \bar{\nu}_\tau$ obtained in the previous Belle measurement with a hadronic $B$ tagging method.

PACS numbers: 13.20.-v, 13.25.Hw
The purely leptonic decay $B^- \to \tau^- \tau^+$ is of particular interest since it provides a direct measurement of the product of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{ub}$ and the $B$ meson decay constant $f_B$. In the Standard Model (SM), the branching fraction of the decay $B^- \to \tau^- \tau^+$ is given by

$$
\mathcal{B}(B^- \to \tau^- \tau^+)_{SM} = \frac{G_F^2 m_B m_{\tau}^2}{8\pi^2} \left(1 - \frac{m_{\tau}^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B,
$$

where $G_F$ is the Fermi coupling constant, $m_{\tau}$ and $m_B$ are the $\tau$ lepton and $B$ meson masses, and $\tau_B$ is the $B^-$ lifetime. The dependence on the lepton mass arises from helicity conservation, which suppresses the muon and electron channels. Observation of $B^- \to \tau^- \tau^+$ could provide a direct measurement of $f_B$. Physics beyond the SM, such as supersymmetry or two-Higgs doublet models, could suppress or enhance $\mathcal{B}(B^- \to \tau^- \tau^+)$ to levels several times as large as the SM expectation through the introduction of a charged Higgs boson $H^\pm$ [3, 4]. The expected SM branching fraction from other experimental constraints is $(0.93^{+0.11}_{-0.12}) \times 10^{-4}$ [5].

The previous Belle measurement [6] reported the first evidence of $B^- \to \tau^- \tau^+$ decay with a significance of 3.5 standard deviations ($\sigma$), and measured the branching fraction to be $\mathcal{B}(B^- \to \tau^- \tau^+) = (1.79^{+0.56}_{-0.59} \text{stat} \pm 0.46 \text{syst}) \times 10^{-4}$, using a full reconstruction tagging method. The BaBar Collaboration has reported a search for $B^- \to \tau^- \tau^+$ decay with hadronic tagging [7] and semileptonic tagging [8] using $383 \times 10^6 B\bar{B}$ pairs. They report a 2.6 $\sigma$ excess, combining the two measurements. No statistically significant enhancement relative to the SM has been observed in previous experimental studies. To establish the $B^- \to \tau^- \tau^+$ signal, test consistency with the SM and search for a charged Higgs boson effect, we need more statistics. In this paper, we present a new measurement of $B^- \to \tau^- \tau^+$ from the Belle experiment with a semileptonic tagging method.

We use a 605 fb$^{-1}$ data sample containing $657 \times 10^6 B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric energy $e^+e^-$ (3.5 on 8 GeV) collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58$ GeV) [9]. We also use a data sample of 68 fb$^{-1}$ taken with a center of mass energy 60 MeV below the nominal $\Upsilon(4S)$ (off-resonance) mass for a background study. 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). Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector was used for the first sample of $152 \times 10^6 B\bar{B}$ pairs, while a 1.5 cm beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining $505 \times 10^6 B\bar{B}$ pairs [10]. The detector is described in detail elsewhere [11].

We use a detailed Monte Carlo (MC) simulation based on GEANT [12] to determine the signal selection efficiency and study the background. In order to reproduce effects of beam background, data taken with random triggers for each run period are overlaid on simulated events. The $B^- \to \tau^- \bar{\nu}_\tau$ signal decay is generated by the EvtGen package [13]. To model the background from $e^+e^- \to B\bar{B}$ and continuum $q\bar{q}$ ($q = u, d, s, c$) production processes, large $B\bar{B}$ and $q\bar{q}$ MC samples corresponding to about four times the data sample are used. We also use MC samples for various rare $B$ decay processes such as charmless hadronic, radiative, electroweak decays and $b \to u$ semileptonic decays. We also use a MC sample for
$e^+e^- \rightarrow \tau^+\tau^-$ events.

The strategy adopted for this analysis is same as in the previous measurements. We reconstruct one of the $B$ mesons decaying semileptonically (referred to hereafter as $B_{\text{tag}}$) and compare the properties of the remaining particle(s) in the event ($B_{\text{sig}}$) to those expected for signal and background. In order to avoid experimental bias, the signal region in data is not examined until the event selection criteria are finalized.

We reconstruct the $B_{\text{tag}}$ in $B^- \rightarrow D^0\ell^+\tau^-$ and $B^- \rightarrow D^0\ell^-\tau^+$ decays. For $D^0$ reconstruction, we use $D^0 \rightarrow D^0\pi^0$ and $D^0\gamma$ decays. $D^0$ mesons are reconstructed in $K^-\pi^+$, $K^-\pi^+\pi^0$ and $K^-\pi^+\pi^-\pi^+$. For $B_{\text{sig}}$, we use $\tau^-$ decays to only one charged particle and neutrinos: $\tau^- \rightarrow \ell^-\pi^-\nu_\tau$ and $\tau^- \rightarrow \pi^-\nu_\tau$. We require that no charged particle or $\pi^0$ remain in the event after removing the particles from the $B_{\text{tag}}$ and $B_{\text{sig}}$ candidates.

Charged particles are selected from well measured tracks reconstructed with the CDC and SVD originating from the interaction point. Electron candidates are identified based on a likelihood calculated using $dE/dx$ in CDC, the response of ACC, ECL shower shape and the ratio of the ECL energy deposit and the track momentum. Muon candidates are selected using KLM hits associated to a charged track. Both muons and electrons are selected with efficiency greater than 90% in the momentum region above 1.2 GeV/c, and misidentification rates of less than 0.2%(1.5%) for electrons (muons). After selecting leptons, we distinguish charged kaons from pions based on a kaon likelihood derived from the TOF, ACC, and $dE/dx$ measurements in the CDC. The typical kaon identification efficiency is more than 85% and the probability of misidentifying pions as kaons is about 8%. Photons are identified as isolated ECL clusters that are not matched to any charged track. $\pi^0$ candidates are selected from pairs of photons with invariant mass between 0.118 and 0.150 GeV/c$^2$. Photons from $\pi^0$ candidates used in $D^0$ meson reconstruction and photons from $D^0 \rightarrow D^0\pi^0\pi^0$ decay are required to pass the following energy requirements: 50 MeV for the barrel, 100 MeV for the forward endcap and 150 MeV for the backward endcap. For low momentum $\pi^0$’s from $D^0 \rightarrow D^0\pi^0\pi^0$ decay, we require the photon energy to be greater than 30 MeV.

$D^0$ meson candidates are selected from combinations of charged kaon, pion and $\pi^0$ candidates. We require the invariant mass of $D^0$ candidates to be in the range $1.851 < M_{D^0} < 1.879$ GeV/c$^2$ for $D^0 \rightarrow K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ decays, and $1.829 < M_{D^0} < 1.901$ GeV/c$^2$ for $D^0 \rightarrow K^-\pi^+\pi^0$ decay. $D^0$ candidates are selected by combining the $D^0$ candidates with low momentum $\pi^0$ candidates and photons. For $D^0$ candidates, we require the mass difference $M^0_{D^0} - M_{D^0}$ to be in the range $0.1389 < M^0_{D^0} - M_{D^0} < 0.1455$ GeV/c$^2$ and $0.123 < M^0_{D^0} - M_{D^0} < 0.165$ GeV/c$^2$ for $D^0 \rightarrow D^0\pi^0\pi^0$ and $D^0 \rightarrow D^0\gamma$ decays, respectively. The regions correspond to $3\sigma$ from the nominal $D^0$ mass or from the nominal mass difference. We select $B_{\text{tag}}$ candidates using the lepton momentum $P^\ell_{\text{tag}}$ and the cosine of the angle between the direction of the $B_{\text{tag}}$ momentum and the direction of the momentum sum of the $D^{(*)0}$ and the lepton $\cos\theta_{B_{\text{tag}}-D^{(*)}\ell}$. This angle is calculated using $\cos\theta_{B_{\text{tag}}-D^{(*)}\ell} = (2E_{\text{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2)/(2P_B \cdot P_{D^{(*)}\ell})$, where $E_{D^{(*)}\ell}$, $P_{D^{(*)}\ell}$ and $M_{D^{(*)}\ell}$ are the energy sum, momentum sum and invariant mass of the $D^{(*)0}$ and lepton. All parameters are calculated in the cms. Here $m_B$ is the nominal $B^-$ mass, and the $P_B$ is the momentum of $B$ meson in the cms calculated with $P_B = \sqrt{E_{\text{beam}}^2 + m_B^2}$. For the signal side track, we require the momentum $P^\tau_{\tau^-\pi^-}$ to be in the region consistent with a $B \rightarrow \tau\tau\pi$ decay. The selection criteria for $B_{\text{tag}}$ and $B_{\text{sig}}$ are optimized for each of the $\tau$ decay modes, because the background levels and the background components are mode-dependent. The optimization is done so that the figure of merit $s/\sqrt{s + n}$ is maximized, where $s$ and $n$ are the number of signal and background events in the signal enhanced region with remaining
energy in the ECL less than 0.2 GeV, which will be described later, calculated with the signal branching fraction of $1.79 \times 10^{-4}$. For leptonic $\tau$ decays, the dominant background is $B\overline{B}$ pair events correctly tagged by a semileptonic decay. Therefore loose selection criteria are chosen to maintain high signal efficiency: $0.5 < P_\ell^* < 2.5$ GeV/$c$, $-2.1 < \cos \theta_{B-D\ell} < 1.3$ for $D^*$ mode or $-2.6 < \cos \theta_{B-D\ell} < 1.2$ for $D^0$ mode, and $0.3$ GeV/$c < P_{\tau-X}^\ast$. For hadronic $\tau$ decay modes, there is more background from $e^+e^- \rightarrow q\bar{q}$ continuum and combinatoric $D^{(*)}\ell$ background. Tighter criteria are used to reduce such backgrounds: $1.0 < P_\ell^* < 2.2$ GeV/$c$, $-1.1 < \cos \theta_{B-D^{(*)}\ell} < 1.1$, and $1.0 < P_{\tau-X}^\ast < 2.4$ GeV/$c$. The upper bound on $P_{\tau-X}^\ast$ is introduced to reject two body $B$ decays. In addition, we suppress continuum background by requiring the cosine of the angle between the signal side pion track and the thrust axis of the $B_{\text{tag}} \cos \theta_{\text{thr}}$ to be less than 0.9.

The most powerful variable for separating signal and background is the remaining energy in the ECL, denoted $E_{\text{ECL}}$, which is the sum of the energies of ECL clusters that are not associated with particles from the $B_{\text{tag}}$ and $B_{\text{sig}}$ candidates. We require a minimum energy threshold of 50 MeV for the barrel and 100 MeV for the forward, and 150 MeV for the backward endcap ECL. A higher threshold is used for the endcap ECL because the effect of beam background is more severe. For signal events, $E_{\text{ECL}}$ must be either zero or a small value arising from residual beam background hits, therefore, signal events peak at low $E_{\text{ECL}}$. On the other hand, background events are distributed toward higher $E_{\text{ECL}}$ due to the contribution from additional particles. We select candidate events in the range $E_{\text{ECL}} < 1.2$ GeV for further analysis.

The dominant background contributions are from $B\overline{B}$ pair and continuum processes, which are estimated to be 86% (59%), 11% (36%) for the leptonic (hadronic) $\tau$ decays from MC, respectively. Background from rare $B$ decays and $\tau$ pair events are estimated from MC to be small (3% for leptonic $\tau$ decays and 4% for hadronic $\tau$ decay) and fixed in the fit to the MC expectation. In order to validate the $E_{\text{ECL}}$ simulation, we use a control sample of double tagged events, where the $B_{\text{tag}}$ is reconstructed in a semileptonic decay as described above and $B_{\text{sig}}$ is reconstructed in the decay chain, $B^- \rightarrow D^{(*)}\ell\bar{\nu} (D^{(*)} \rightarrow D^0 \pi^0)$, followed by $D^0 \rightarrow K^-\pi^+$. The dominant source affecting the $E_{\text{ECL}}$ distribution in the control sample is beam background hits and is common to the signal. Figure 1 shows the $E_{\text{ECL}}$ distribution in the control sample for data and the MC simulation scaled to the same luminosity. The background in this control sample is negligibly small. The agreement between data and MC demonstrates the validity of the $E_{\text{ECL}}$ simulation in the signal MC. The $E_{\text{ECL}}$ background shape is validated using the $E_{\text{ECL}}$ sideband region defined by $0.4 < E_{\text{ECL}} < 1.2$ GeV and off-resonance data. We confirm the background shapes obtained from MC agree with the $E_{\text{ECL}}$ shape of these background data samples.

After finalizing the signal selection criteria, the signal region is examined. The number of signal events is extracted from an extended maximum likelihood fit to the $E_{\text{ECL}}$ distribution. Probability density functions (PDFs) for each $\tau$ decay mode are constructed from the MC simulation. We use $E_{\text{ECL}}$ histograms obtained from MC samples for each of the signal and the background components. The PDFs are combined into a likelihood function,

$$\mathcal{L} = \frac{e^{-\sum_n n_j} N \prod_{i=1}^N \sum_{j} n_j f_j(E_i)}{N!} \quad (2)$$

where $E_i$ is the $E_{\text{ECL}}$ value in the $i$th event, $N$ is the total number of events in the data, and $n_j$ is the yield of the $j$th component, where $j$ is an index for the signal and background contributions. In the final fit, four parameters are floated: the signal yield and the sum of
FIG. 1: $E_{\text{ECL}}$ distribution for double semileptonic tagged events. The points with error bars are for data and the solid histogram is the MC expectation.

| Decay Mode | Signal Yield | $\varepsilon$ | $B$ |
|------------|--------------|---------------|-----|
| $\tau^- \to e^- \nu \bar{\nu}_\tau$ | $78_{-22}^{+23}$ | $5.9 \times 10^{-4}$ | $(2.02_{-0.70}^{+0.69}) \times 10^{-4}$ |
| $\tau^- \to \mu^- \nu \bar{\nu}_\tau$ | $15_{-17}^{+18}$ | $3.7 \times 10^{-4}$ | $(0.62_{-0.71}^{+0.76}) \times 10^{-4}$ |
| $\tau^- \to \pi^- \nu \bar{\nu}_\tau$ | $58_{-20}^{+21}$ | $4.7 \times 10^{-4}$ | $(1.88_{-0.71}^{+0.70}) \times 10^{-4}$ |
| Combined | $154_{-35}^{+36}$ | $14.3 \times 10^{-4}$ | $(1.65_{-0.37}^{+0.38}) \times 10^{-4}$ |

**TABLE I:** Results of the fit for signal yields and branching fractions.

$B\bar{B}$ and continuum backgrounds for the three $\tau$ decay modes. We combine $\tau$ decay modes by constraining the ratios of the signal yields to the ratio of reconstruction efficiencies obtained from MC. Figure 2 shows the $E_{\text{ECL}}$ distribution obtained with the fit results. $E_{\text{ECL}}$ distributions for each $\tau$ decay mode is also shown. We see a clear excess of signal events in the region near $E_{\text{ECL}} \sim 0$. We obtain the signal yield to be $n_s = 154_{-35}^{+36}$. The branching fraction is calculated as $B = n_s / (2 \cdot \varepsilon \cdot N_{B^+ B^-})$, where $\varepsilon$ is the reconstruction efficiency including the tagging efficiency and the branching fraction of the $\tau$ decay modes and $N_{B^+ B^-}$ is the number of $\Upsilon(4S) \to B^+ B^-$ events, assuming $N_{B^+ B^-} = N_{B^0 \bar{B}^0}$. Table I shows the signal yields and the branching fractions obtained from separate fits for each $\tau$ decay mode and fits with all three modes combined.

Systematic errors for the measured branching fraction are associated with the uncertainties in the signal yield, efficiencies and number of $B^+ B^-$ pairs. The systematic errors for the signal yield arise from the uncertainties in the PDF shapes for the signal ($^{+3.1}_{-3.2}\%$) and for the background ($^{+11.8}_{-11.2}\%$) which are dominated by MC statistics. For the latter, uncertainties in the branching fractions of $B$ decay modes that peak at $E_{\text{ECL}} = 0$ such as $B^- \to D^0 l^+ \nu$...
with $D^0 \to K^0_L \pi^0, K^0_L K^0_L$ and so on ($^{+4.2}_{-3.1}$)%, as well as uncertainties in the background from rare $B$ decays and $\tau$ pair events (3.8%) are also taken into account. We take a 11.6% error as the systematic error associated with the tag reconstruction efficiency from the difference of yields between data and MC for the control sample. This value includes the error in the branching fraction $B(B^- \to D^{*0}(\ell^- \bar{\nu}))$, which we estimate from $B(B^0 \to D^{*+}(\ell^+ \nu))$ in Ref. [14] and isospin symmetry. The systematic error in the signal efficiencies arises from the uncertainty in tracking efficiency (1.0%), particle identification efficiency (1.3%), branching fractions of $\tau$ decays (0.4%), and MC statistics (0.9%). The systematic error due to the uncertainty in $N_{B^+ B^-}$ is 1.4%. The total fractional systematic uncertainty is $^{+21}_{-22}$%, and the branching fraction is

$$B(B^- \to \tau^- \bar{\nu}_\tau) = (1.65^{+0.38}_{-0.37}(\text{stat})^{+0.35}_{-0.37}(\text{syst})) \times 10^{-4}.$$  

(3)

The significance of the observed signal is evaluated by $\Sigma = \sqrt{-2 \ln(L_0/L_{\text{max}})}$ where $L_{\text{max}}$

![FIG. 2: $E_{\text{ECL}}$ distribution of semileptonic tagged events with the fit result for (a) all $\tau$ decay modes combined, (b) $\tau^- \to e^- \nu_e \bar{\nu}_\tau$, (c) $\tau^- \to \mu^- \nu_\mu \bar{\nu}_\tau$ and (d) $\tau^- \to \pi^- \nu_\tau$. The points with error bars are data. The hatched histogram and solid open histogram are the background and the signal, respectively.](image)
and $L_0$ denote the maximum likelihood value and likelihood value obtained assuming zero signal events, respectively. The systematic uncertainty is convolved in the likelihood with a Gaussian distribution with a width corresponding to the systematic error of the signal yield. We determine the significance of the signal yield to be 3.8.

In summary, we have measured the decay $B^- \rightarrow \tau^- \bar{\nu}$ with $B\bar{B}$ pair events tagged by semileptonic $B$ decays using a data sample containing $657 \times 10^6$ $B\bar{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric $e^+e^-$ collider. We measure the branching fraction to be $(1.65^{+0.36}_{-0.37}^{(\text{stat})}^{+0.35}_{-0.37}^{(\text{syst})}) \times 10^{-4}$, with a significance of 3.8 standard deviations including systematics. We confirm the evidence reported in the previous Belle measurement with $B\bar{B}$ pair events tagged by hadronic $B$ decays. Using the measured branching fraction and known values of $G_F, m_B, m_\tau$ and $\tau_B$ [14], the product of the $B$ meson decay constant $f_B$ and the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{ub}|$ is determined to be $f_B|V_{ub}| = (9.7 \pm 1.1^{+1.0}_{-1.1}) \times 10^{-4}$ GeV. The measured branching fraction is consistent with the SM expectation from other experimental constraints [5].

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and SINET3 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Natural Science Foundation of China under contract No. 10575109 and 10775142; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

[1] Throughout this paper, the inclusion of the charge conjugate mode decay is implied unless otherwise stated.
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