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Rare decays of the tau lepton at Belle*

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Abstract We report recent results of searches for lepton flavor violation and second class current in decays of τ leptons using the data sample collected in the Belle experiment at the KEKB electron-positron asymmetric-energy collider.

Key words tau lepton, flavor violation, rare decays, second class current

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1 Introduction

The vast number of τ-pairs that have been collected at nowadays B-factories allow for searches for increasingly rare decays of the τ lepton. In the case of lepton-flavor-violating (LFV) decay modes, such searches are equivalent to a search for New Physics. On the other hand searches for second class current decays could solve a long standing question of weak interactions.

In section 2 we will give an overview of recent searches in several LFV decay modes using the data sample collected in the Belle experiment at the KEKB electron-positron asymmetric-energy collider[1]. Recent results of searches for the second class current reactions $\tau \to \nu\pi\eta$ and $\tau \to \nu\pi\eta'(958)$ are presented in section 3.

2 Lepton flavor violation in tau lepton decays

Lepton flavor violation in charged lepton decays is forbidden in the Standard Model (SM) or highly suppressed if neutrino mixing is included. However, LFV appears in various extensions of the SM such as supersymmetry models, leptoquark models and others [2–9]. Some of these models predict branching fractions ($\mathcal{B}$) which, for certain combinations of model parameters, can be as high as 10^{-7} which is already accessible in high-statistics B-factory experiments. Since the mass of the τ is high enough to allow decays into hadrons, many different decay modes can be studied. In total, LFV searches have been performed in 48 τ decay modes at Belle and BABAR. Here, we summarize the results of new or recently updated searches at Belle: $\tau^- \to l^-l^+l^-$ ($l^\pm = e^\pm$ or $\mu^\pm$), $\tau^- \to l^-K_S^0$, $\tau^- \to l^-K_S^0K_S^0$, $\tau^- \to l^-h^+h'^-$ [10] and $\tau^- \to l^-f_0(980)$ [11]. Unless otherwise stated, charge-conjugate decays are included throughout this paper.

2.1 Event selection for LFV searches

Given the summary character of this paper only a general outline of the event selection and analysis procedure is given in the following. Detailed descriptions can be found elsewhere [10, 11]. Since almost all of the τ leptons decay into one or three prongs, we can select τ-pair events by requiring a low track multiplicity. In the center of mass (CM) frame, events are divided into two hemispheres corresponding to signal and tag sides by the plane perpendicular to the thrust axis [12]. We search for $\tau^+\tau^-$ events in which one of the τ (signal side) decays into a LFV mode while the τ on the tag side decays into one charged particle plus one or two neutrinos. This tagging requirement significantly reduces background from $B\bar{B}$ and $q\bar{q}$ events. The good lepton identification capabilities of the Belle detector play a crucial role for these searches because all the studied LFV decay modes contain at least one electron or muon. The rate of pions faking electrons and muons is below 0.5% and 3%, respectively. Since we require that all the particles on the signal side are reconstructed in the detector, all

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the missing energy originates from the escaping neutrinos from the τ decay on the tag side. This allows to significantly suppress the background from generic $\tau^-\tau^+$ events using energy and momentum conservation.

In order to extract the signal from LFV decays, the invariant mass $M_{\rm inv}$ on the signal side and the difference between the energy on the signal side and the beam energy in the CM system, ΔE, are used. As illustrated in Fig. 1, which shows the $M_{\rm inv}$–ΔE plane for $\tau \to l\,\pi^+\pi^-$ events, signal events should have $M_{\rm inv}$ close to the τ mass and ΔE close to 0.

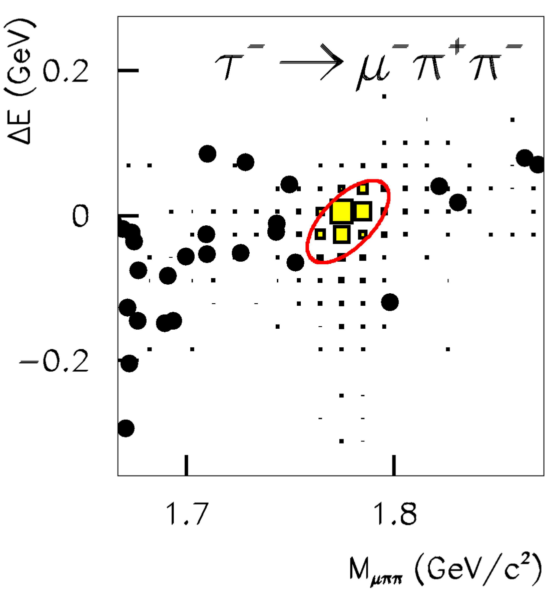

Fig. 1. Scatter plot of data in the $M_{\rm inv} - \Delta E$ plane for $\tau \to \mu^-\pi^+\pi^-$. Data is indicated by the solid circles. The filled boxes show the MC signal distribution with arbitrary normalization. The elliptical region shown by the solid curve contains 90% of the signal and is used for evaluating the signal yield. The region outside the signal region is used to estimate backgrounds from data[10].

To avoid bias in the event selection, the region containing 90% of the signal is blinded until the event selection is finalized and the number of expected background events is determined. Expected background rates are estimated using the remaining data events in the side band region which is defined as the area around the signal region in Fig. 1. Finally, the blinded region is uncovered and if no significant excess over the estimated background is found in data, an upper limit for the number of signal events at a 90% confidence level (C. L.), s_{90}, is calculated using the POLE program[13] which is an implementation of the Feldman-Cousins method[14].

The upper limit on the branching fraction is then given by

$$\mathcal{B} < \frac{s_{90}}{2\epsilon N_{\tau\tau}}\,, \qquad (1)$$

where ϵ is the signal efficiency and $N_{\tau\tau}$ is the number of τ-pairs given by the integrated luminosity times the cross section of the τ-pair production.

2.2 Tau decays into three leptons

Previous searches for LFV of $\tau^- \to l^-l^+l^-$ at Belle [15] and BABAR [16] have reached upper limits of the order of 10^{-8} for the branching ratio. The limits shown in the following correspond to the results of an updated analysis using 782 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and 60 MeV below. The dominant backgrounds for these modes are the Bhabha process and the two photon process $e^+e^- \to e^+e^-\mu^+\mu^-$. Table 1 summarizes the results for all $\tau^- \to l^-l^+l^-$ modes.

Table 1. Results for $\tau^- \to l^-l^+l^-$ modes. The expected numbers of background events are estimated using data events in the $M_{\rm inv} - \Delta E$ plane excluding the signal region (see example in Fig. 1). Since no excess over background is found, 90% C. L. upper limits are given.

mode	$\epsilon(\%)$	$N_{\rm BG}$	$\sigma_{\rm syst}$	$N_{\rm obs}$	$\mathcal{B}(\times 10^{-8})$
$e^-e^+e^-$	6.0	0.21 ± 0.15	9.8	0	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13 ± 0.06	7.4	0	2.1
$e^-\mu^+\mu^-$	6.1	0.10 ± 0.04	9.5	0	2.7
$\mu^-e^+e^-$	9.3	0.04 ± 0.04	7.8	0	1.8
$e^+\mu^-\mu^-$	10.1	0.02 ± 0.02	7.6	0	1.7
$\mu^+e^-e^-$	11.5	0.01 ± 0.01	7.7	0	1.5

No events are found in the signal region for any mode and therefore upper limits at 90% C. L. in the range $\mathcal{B}(\tau^- \to l^-l^+l^-) < (1.5-2.7)\times 10^{-8}$ can be given. These are the best current upper limits for LFV from τ decays.

2.3 $\tau^- \to l^-\ K_S^0$ and $\tau^- \to l^-\ K_S^0\ K_S^0$

Searches for LFV in $\tau^- \to l^-K_S^0$ have been performed previously at Belle [17] and BABAR [18]. Best previous upper limits for $\tau^- \to l^-\ K_S^0\ K_S^0$ on the other hand originate from the CLEO experiment using 13.9 fb^{-1} of data [19]. In this paper, we summarize an updated search for the LFV decays $\tau^- \to l^-K_S^0$ and a search for $\tau^- \to l^-\ K_S^0\ K_S^0$ using 671 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and 60 MeV below. The dominant background here is due to $q\bar{q}$ events containing real K_S^0 and a $\pi^\pm$ misidentified as a lepton. Results for all modes are listed in Table 2.

Table 2. Results for $\tau \to l\ K^0_S$ and $\tau \to l\ K^0_S\ K^0_S$ modes. The expected numbers of background events are estimated using data events in the $M_{\rm inv}-\Delta E$ plane excluding the signal region (see example in Fig. 1). Since no excess over background is found, 90% C. L. upper limits are given.

mode	$\epsilon(\%)$	$N_{\rm BG}$	$\sigma_{\rm syst}$	$N_{\rm obs}$	$\mathcal{B}(\times10^{-8})$
$e^-K^0_S$	10.2	0.18 ± 0.18	6.6	0	2.6
$\mu^-K^0_S$	10.7	0.35 ± 0.21	6.8	0	2.3
$e^-K^0_S\ K^0_S$	5.82	0.07 ± 0.07	11.2	0	7.1
$\mu^-K^0_S\ K^0_S$	5.08	0.12 ± 0.08	11.3	0	8.0

No events are found in the signal region for any mode and therefore upper limits at 90% C. L. in the range $\mathcal{B}(\tau^-\to l^-K^0_S)<(2.3-2.6)\times10^{-8}$ and $\mathcal{B}(\tau^-\to l^-\ K^0_S\ K^0_S)<(7.1-8.0)\times10^{-8}$ can be given which are an improvement over previous limits for all modes. The limits for $\tau^-\to l^-\ K^0_S\ K^0_S$ correspond to an improvement by a factor of 31−43 with respect to the CLEO limits.

2.4 $\tau^-\to l^-h^+h'^-$

Searches for LFV of $\tau^-\to l^-h^+h'^-$ ($h,h'=\pi^\pm$ or $K^\pm$) have been performed previously at Belle [20] and BABAR [21]. The limits shown in this paper correspond to an updated analysis using 671 fb^{-1} of data collected at the $\Upsilon(4S)$ resonance and 60 MeV below. The background for these modes consists dominantly of $q\bar{q}$ events and events from $\tau^-\to\nu\pi^-\pi^+\pi^-$ where one of the $\pi^\pm$ is misidentified as a lepton. Results for all modes are given in Table 3. Since no significant excess over the estimated background is found for any mode, upper limits in the range $\mathcal{B}^-(\tau\to l^-hh')<(3.3-16)\times10^{-8}$ at 90% C. L. can be given [10] which are the best available limits for each mode.

2.5 $\tau^-\to l^-f_0(980)$

The results presented in the following establish the first experimental limits for the LFV decay modes $\tau^-\to l^-f_0(980)$ [11]. These decay modes are currently among the best channels for indirect testing for the Higgs boson [9] because their branching ratios can be enhanced in SUSY models by Higgs mediation.

Events from $e^+e^-\to q\bar{q}$ and $e^+e^-\to e^+e^-q\bar{q}$ constitute the main background for the $\tau^-\to l^-f_0(980)$ decays modes. Results for both modes are summarized in Table 4. Since no events are found in the signal region for both modes, upper limits

$$\mathcal{B}(\tau^-\to\mu^-f_0(980))\times\mathcal{B}(f_0(980)\to\pi^+\pi^-)<3.2\times10^{-8}$$

and

$$\mathcal{B}(\tau^-\to e^-f_0(980))\times\mathcal{B}(f_0(980)\to\pi^+\pi^-)<3.4\times10^{-8}$$

at 90% C. L. can be given.

Table 3. Results for $\tau\to lhh'$. The expected numbers of background events are estimated using data events in the $M_{\rm inv}-\Delta E$ plane excluding the signal region (see example in Fig. 1). Since no significant excess over background is found, 90% C. L. upper limits are given [10]

mode	$\epsilon(\%)$	$N_{\rm BG}$	$\sigma_{\rm syst}$	$N_{\rm obs}$	$\mathcal{B}(\times10^{-8})$
$\mu^-\pi^+\pi^-$	3.69	1.12 ± 0.38	5.9	0	3.3
$\mu^+\pi^-\pi^-$	3.84	0.73 ± 0.25	5.9	0	3.7
$e^-\pi^+\pi^-$	3.99	0.34 ± 0.15	6.0	0	4.4
$e^+\pi^-\pi^-$	3.91	0.10 ± 0.07	6.0	1	8.8
$\mu^-K^+K^-$	2.40	0.52 ± 0.23	6.7	0	6.8
$\mu^+K^-K^-$	2.07	0.00 ± 0.06	6.8	0	9.6
$e^-K^+K^-$	3.50	0.11 ± 0.08	6.5	0	5.4
$e^+K^-K^-$	3.28	0.05 ± 0.05	6.6	0	6.0
$\mu^-\pi^+K^-$	2.63	0.67 ± 0.14	6.3	2	16
$e^-\pi^+K^-$	3.02	0.33 ± 0.19	6.4	0	5.8
$\mu^-K^+\pi^-$	2.60	1.04 ± 0.32	6.3	1	10
$e^-K^+\pi^-$	2.98	0.57 ± 0.19	6.4	0	5.2
$\mu^+K^-\pi^-$	2.61	1.37 ± 0.21	6.3	1	9.4
$e^+K^-\pi^-$	2.83	0.10 ± 0.07	6.4	0	6.7

Table 4. Results for $\tau\to l f_0(980)$. The expected numbers of background events are estimated using data events in the $M_{\rm inv}-\Delta E$ plane excluding the signal region (see example in Fig. 1). Since no excess over background is found, 90% C. L. upper limits are given [11].

mode	$\epsilon(\%)$	$N_{\rm BG}$	$\sigma_{\rm syst}$	$N_{\rm obs}$	$\mathcal{B}(\times10^{-8})$
$e^-f_0(980)$	5.80	0.10 ± 0.07	11.5	0	3.4
$\mu^-f_0(980)$	6.02	0.11 ± 0.08	10.8	0	3.2

3 Second class current

Half a century ago Weinberg [22] classified the weak charged current according to its G-parity transformation properties into first class current with $PG(-1)^J=1$ and second class current $PG(-1)^J=-1$ where P is the parity, G is the G-parity and J is the spin. So far only first class current reactions have been observed. In the SM, the second class current is assumed to be small and it vanishes in the limit of isospin symmetry. In the following two searches for the second class current reactions $\tau^-\to\nu\pi^-\eta$ and $\tau^-\to\nu\pi^-\eta'(958)$ at Belle are presented, both using 670 fb^{-1} of data. Theoretical predictions for the branching ratios of these decay modes are of the order of $10^{-6}-10^{-5}$ [23, 24]

3.1 $\tau^- \to \nu\pi^-\eta$

$\tau^- \to \nu\pi^-\eta$ candidate events are selected in the $\eta \to \pi^+\pi^-\pi^0$ mode by requiring three charged pions on the signal side with an additional π^0 reconstructed from two γ and a leptonic decay on the tag side.

The number of η candidates, $N_\eta^{\rm fit}$, is extracted from the spectrum of the three pion mass, $M_{3\pi}$, which is shown in Fig. 2.

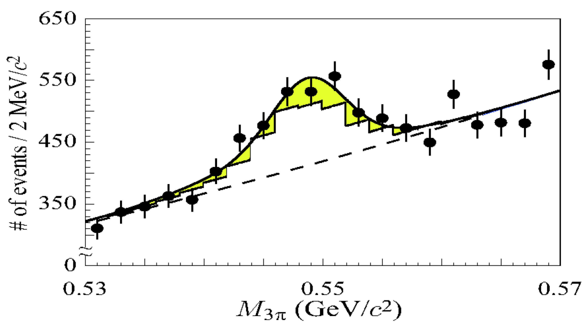

Fig. 2. Three pion mass distribution. The full and the dashed curve indicate the fit result and the combinatorial background, respectively. The histogram shows contributions from background events containing η.

Fitting the spectrum with the sum of three Gaussians which represent the signal and a second order polynomial function for the combinatorial background results in $N_\eta^{\rm fit} = 749.2 \pm 67.3$. Contributions to $N_\eta^{\rm fit}$ from $\tau^- \to \nu\pi^-\pi^0\eta$, $\tau^- \to \nu\ K^{*-}\pi^0\eta$, $\tau^- \to \nu\ K^-\eta$ and $q\bar{q}$ events are evaluated using MC based on the recent precise measurement of the branching ratios of these τ decay modes [25]. After background subtraction we obtain 190.9 ± 68.6 signal events. The signal detection efficiency is evaluated to be 4.4% and the total systematic uncertainty is 17.6% with the largest contribution coming from the error of the branching fraction of $\tau^- \to \nu\pi^-\pi^0\eta$. This results in $\mathcal{B}(\tau^- \to \nu\pi^-\eta) = (4.4\pm1.6\pm0.8)\times10^{-5}$ where the first and second errors are the statistical and systematic uncertainties. The signal significance $(2.4\,\sigma)$ does not allow for a conclusive observation claim and therefore an upper limit at 90% C. L. of

$$\mathcal{B}(\tau^- \to \nu\pi^-\eta) < 7.3\times10^{-5} \quad (2)$$

is given which is an improvement over the previous upper limit obtained by the CLEO experiment[26].

3.2 $\tau^-\!\to\nu\pi^-\eta'(958)$

In order to search for $\tau^- \to \nu\pi^-\eta'$ candidate events with $\eta' \to \pi^+\pi^-\eta$ and $\eta \to \gamma\gamma$, similar selection criteria as for $\tau^- \to \nu\pi^-\eta$ are applied. The obtained number of η', $N_{\eta'} = -2.9^{+24.5}_{-23.7}$, is consistent with zero and therefore an upper limit $\mathcal{B}(\tau^- \to \nu\pi^-\eta') < 4.6\times10^{-6}$ at 90% C. L. is given. This limit is an improvement over the previous best upper limit obtained by the BABAR experiment[27].

4 Summary

Searches for lepton flavor violation in τ decays have been performed in many decay modes using the data collected with the Belle experiment. Since no evidence has been found in any mode, upper limits at 90% confidence level are given:

$$\mathcal{B}(\tau^- \to l^-l^+l^-) < (1.5-2.7)\times10^{-8}$$

$$\mathcal{B}(\tau^- \to l^-K_S^0) < (2.3-2.6)\times10^{-8}$$

$$\mathcal{B}(\tau^- \to l^-K_S^0K_S^0) < (7.1-8.0)\times10^{-8}$$

$$\mathcal{B}(\tau^- \to l^-h^+h'^-) < (3.3-16)\times10^{-8}$$

$$\mathcal{B}(\tau^- \to l^-f_0)\times\mathcal{B}(f_0 \to \pi^+\pi^-) < (3.2-3.4)\times10^{-8}$$

For every mode, these are the best currently available limits.

Further, searches for the second class current reactions $\tau^- \to \nu\pi^-\eta$ and $\tau^- \to \nu\pi^-\eta'(958)$ have been performed. No significant excess over background expectations has been found and therefore the upper limits $\mathcal{B}(\tau^- \to \nu\pi^-\eta) < (4.4\pm1.6\pm0.8)\times10^{-5}$ and $\mathcal{B}(\tau^- \to \pi^-\eta') < 4.6\times10^{-6}$ are given at 90% C. L..

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