SLAC-PUB-13006

Lepton Flavour Violation and Baryon Number Non-conservation in $\tau \rightarrow \Lambda + h$

G. D. Lafferty[a] on behalf of the *BABAR* Collaboration

[a]School of Physics and Astronomy,
The University of Manchester,
Manchester M13 9PL, UK

We have searched for the violation of baryon number B and lepton number L in the $(B-L)$-conserving modes $\tau^- \rightarrow \overline{\Lambda}\pi^-$ and $\tau^- \rightarrow \overline{\Lambda}K^-$ as well as the $(B-L)$-violating modes $\tau^- \rightarrow \Lambda\pi^-$ and $\tau^- \rightarrow \Lambda K^-$ using 237 fb^{-1} of data collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings. We do not observe any signal and we determine preliminary upper limits on the branching fractions $\mathcal{B}(\tau^- \rightarrow \overline{\Lambda}\pi^-) < 5.9 \times 10^{-8}$, $\mathcal{B}(\tau^- \rightarrow \Lambda\pi^-) < 5.8 \times 10^{-8}$, $\mathcal{B}(\tau^- \rightarrow \overline{\Lambda}K^-) < 7.2 \times 10^{-8}$, and $\mathcal{B}(\tau^- \rightarrow \Lambda K^-) < 15 \times 10^{-8}$ at 90% confidence level.

1. INTRODUCTION

One of the important unresolved issues in physics is the presence of a large baryon asymmetry in today's universe. According to Sakharov [1] three conditions must be satisfied in order for a baryon asymmetry to arise from an initial state with zero baryon number: baryon number violation, C and CP symmetry violation, and a departure from thermal equilibrium. No baryon number violating processes have yet been observed [2]. Although we know that the baryon number was violated in the early universe we do not know how this came about. Conservation of angular momentum requires that the spin 1/2 of a nucleon that is decaying to a lepton be transferred to the lepton: $\Delta B = \pm\Delta L$. Therefore there are two types of baryon instabilities $|\Delta(B-L)| = 0$ or 2. In the Standard Model (SM), and in most of its extensions, it is required that $\Delta(B-L) = 0$. The second possibility of $|\Delta(B-L)| = 2$ allows transitions with $\Delta B = -\Delta L$, or $|\Delta B| = 2$ and $|\Delta L| = 0$, or $|\Delta L| = 2$ and $|\Delta B| = 0$. It follows that the conservation or violation of $(B-L)$ determines the mechanism of baryon instability.

It has been shown that, in baryogenesis, non-perturbative Standard Model effects at the electroweak energy scale will erase any baryon excess generated by $(B-L)$-conserving processes at the earliest moments of the universe ($T \gg 1$ TeV) [3]. In addition, generating a baryon excess through electroweak effects alone does not seem to be adequate to account for the observed baryon asymmetry [4]. A component with $\Delta(B–L) = 2$ might be necessary to explain baryogenesis.

Most existing searches for $(B–L)$ violation have been restricted to experiments with nucleons [2]. In this analysis we search for the decays $\tau \rightarrow \Lambda\pi$ and $\tau \rightarrow \Lambda K$, in the $(B-L)$-conserving modes $\tau^- \rightarrow \overline{\Lambda}\pi^-(K^-)$ as well as the $(B-L)$-violating modes $\tau^- \rightarrow \Lambda\pi^-(K^-)$. Charge conjugate modes are always included if not mentioned otherwise. A similar analysis of the modes $\tau \rightarrow \Lambda\pi$ published recently by the Belle Collaboration [5] finds the upper limits $\mathcal{B}(\tau^- \rightarrow \overline{\Lambda}\pi^-) < 14 \times 10^{-8}$ and $\mathcal{B}(\tau^- \rightarrow \Lambda\pi^-) < 7.2 \times 10^{-8}$ at 90% confidence level (CL).

Experimental limits on the proton lifetime imply that the expected branching fraction for $\tau \rightarrow (\overline{p} + \text{anything})$ is not observable in the Standard Model: $\mathcal{B}(\tau \rightarrow \overline{p} + X) < 10^{-40}$ [6]. The Λ baryon couples weakly to the proton. We would then expect approximately 10^8 times weaker [6] constraints from the proton lifetime for $\tau \rightarrow \Lambda\pi(K)$. A recent theoretical paper [7] studied dimension-6 operators and concludes that baryon number violation in decays involving higher generations,

Contributed to 9th International Workshop on Tau Lepton Physics (Tau06), 09/19/2006--9/22/2006, Pisa, Italy

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

assuming proton stability, will not be observable. However such a model may not be adequate to describe the apparent baryon asymmetry in the first place. Models with dimension-9 operators and yet unknown mechanisms that generate baryon number violation or enhance the coupling to higher generations may be able to accomplish this [8].

With the advent of the B factories, which also produce large quantities of τ leptons, we are now able to study such decays experimentally with greatly improved precision.

2. THE *BABAR* DETECTOR AND THE DATASET

The measurements presented here were performed using data collected by the *BABAR* detector [9] at the PEP-II storage rings. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT), consisting of 5 layers of double-sided detectors, and a 40-layer central drift chamber (DCH), both operating in a 1.5 T axial magnetic field. Charged particle identification is provided by the energy loss in the tracking devices and by the measured Cherenkov angle from an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. Photons and electrons are detected by a CsI(Tl) electromagnetic calorimeter (EMC). The EMC is surrounded by an instrumented flux return (IFR). Electrons are identified using measurements from the DCH, EMC, and DIRC. The average identification efficiency is approximately 97%, whereas the pion (kaon) misidentification rate is less than 2% (1%). Kaons are identified using the SVT, DCH, and DIRC. The average identification efficiency for the tight kaon selection is approximately 80%, whereas the pion misidentification rate is less than 1%. The average identification efficiency for the loose kaon selection is approximately 90%, whereas the pion misidentification rate is less than 4%. Protons are identified with a likelihood-based algorithm using measurements from all detector components described above. The proton identification efficiency ranges from approximately 90% to 96% depending on polar angle and momentum, whereas the average pion (kaon) misidentification rate is 5% (12%).

The data sample used for the present analysis corresponds to an integrated luminosity of 237 fb^{-1} collected from e^+e^- collisions at, or 40 MeV below, the $\Upsilon(4S)$ resonance. Production and decay of the tau leptons are simulated with the kk2f [10,11] and tauola [12,13] Monte Carlo (MC) event generators, taking spin correlations into account for the signal mode. B-meson decays are simulated with the EvtGen generator [14], and $q\overline{q}$ events, where $q = u, d, s,$ or c quark, with the JETSET [15] generator. The detector is fully modelled using the GEANT4 simulation package [16].

3. ANALYSIS METHOD

We reconstruct candidate events $e^+e^- \to \tau^+\tau^-$ with one τ decaying to $\Lambda\pi(K)$ and $\Lambda \to p\pi$. The other tau in each event is required to be a one-prong decay. Decays that conserve $(B–L)$ are recognized by opposite sign charge of the pion or kaon from the τ decay and the pion from the Λ decay. In decays where $(B–L)$ is violated the two charges have the same sign.

Each event must have exactly four well reconstructed tracks in the fiducial volume of the DCH with a total charge of zero. We divide the events into two hemispheres defined by the thrust axis of the event. The thrust axis is calculated using tracks in the drift chamber and calorimeter energy deposits without an associated track. We require that the three signal tracks are contained in one hemisphere and that there is exactly one remaining track in the other hemisphere, which we will refer to as the tagging hemisphere.

One of the signal tracks must be identified as a proton and, when combined with an oppositely charged signal track, must give a $p\pi^-$ invariant mass within 5 MeV/c^2 of the nominal Λ mass [2]. The set of signal tracks is subjected to a topological fit to the decay tree $\tau \to \Lambda\pi(K)$, which must converge and return a χ^2 probability greater than 2.5%.

We require that the center-of-mass (CM) momentum of the Λ is greater than the lower kinematic limit of 1.8 GeV/c for $\tau^- \to \Lambda\pi^-$ decays. A requirement on the Λ flight distance $L_\Lambda > 1$ cm and the signed flight length significance $L_\Lambda/\sigma_\Lambda > 0$ removes $\tau^+\tau^-$ (88%) and $q\overline{q}$ (22%) events that do not contain true Λ particles. The remaining backgrounds are mostly from $q\overline{q}$ events and to a lesser degree $\tau^+\tau^-$ events that contain $K^0_{\rm s}$ decays and photon conversions $\gamma \to e^+e^-$. None of approximately 800 million Monte Carlo $B\overline{B}$ events survives the selection criteria.

It is found that the Λ momentum spectrum is not very well described by the MC simulation, most likely due to imperfections of the $q\overline{q}$ MC event generator. For this reason the final background is determined from the data. All other variables that were studied show better agreement between data and MC.

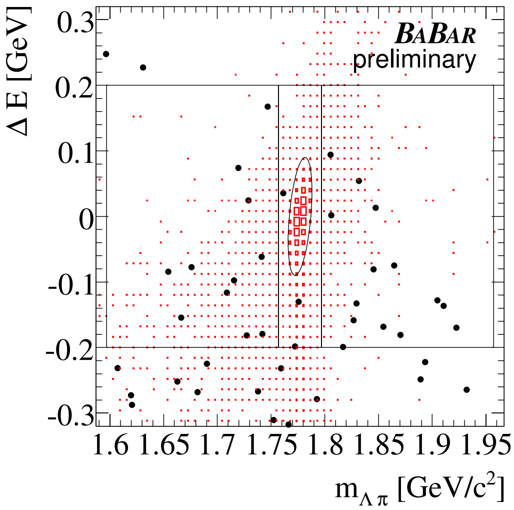
We require that the pion track from the Λ decay, and the tagging track from the other τ lepton, do not pass tight kaon identification requirements. In the mode $\tau \to \Lambda\pi$ we require that the π is not identified as a kaon. In the mode $\tau \to \Lambda K$ we require that the kaon track be identified with loose kaon identification requirements. To suppress candidates that include tracks from photon conversions, we require that neither the pion or kaon from the τ decay nor the pion from the Λ decay be identified as an electron. The pion or kaon from the τ decay must not be identified as a proton.

We study events in the two dimensional plane $m_{\Lambda\pi(K)}$ versus $\Delta E_{\Lambda\pi(K)}$, where $m_{\Lambda\pi(K)}$ is the invariant mass of the Λ and the pion (or kaon) candidate, and $\Delta E_{\Lambda\pi(K)} = E_{\Lambda\pi(K)} - \sqrt{s}/2$ is the reconstructed energy $E_{\Lambda\pi(K)}$ of the signal tracks minus the expected τ energy, which is half the known e^+e^- center-of-mass energy $\sqrt{s}$. A rectangular region that includes the signal region was blinded during the development of the analysis. Signal candidates are counted in an elliptical signal region with a half width of 10 MeV in $m_{\Lambda\pi(K)}$ and 90 MeV in $\Delta E_{\Lambda\pi(K)}$ centered around the nominal τ mass and $\Delta E_{\Lambda\pi(K)} = 0$. In the case of $\tau \to \Lambda K$ the width in $m_{\Lambda\pi(K)}$ is reduced to 7 MeV because of the better resolution in this mode. The elliptical signal region is slightly tilted to reflect the small correlation between the two variables. The tilt is $\approx 3^\circ$, which can also be expressed as a correlation coefficient between the two variables: $\rho = 0.42$ for $\tau \to \Lambda\pi$ and $\rho = 0.56$ for $\tau \to \Lambda K$. The definition of the signal region as well as the other selection requirements applied in this analysis have been optimized using MC simulation, to obtain the lowest average upper limit for the signal modes under the assumption that no signal will be observed.

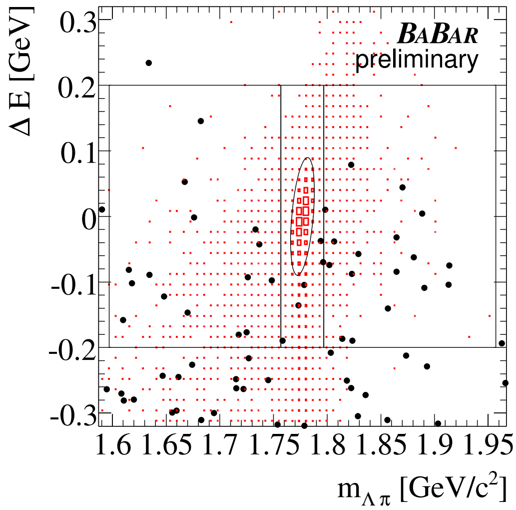
We estimate the number of background events in the signal region with a two-dimensional unbinned maximum likelihood fit of the $m_{\Lambda\pi(K)}$ and $\Delta E_{\Lambda\pi(K)}$ distributions outside the blinded region. We try a number of functional forms that describe both the data and MC distributions. The default fit uses a simple parametrization that describes the data well and results in a background estimate that is in the center of the possible range of values. A first-order polynomial is fitted to the $m_{\Lambda\pi(K)}$ distribution and a Gaussian function to the $\Delta E_{\Lambda\pi(K)}$ distribution. The blinded region is excluded from the fit and the probability density function is set to zero within the blinded region. The elliptical signal regions and the blinded region are indicated in Figure 1. Due to the uncertainties of the background parametrization and the possibility of correlations among the fit variables, we take a conservative 100% error on the number of estimated background events in the signal region.

4. SELECTION EFFICIENCY

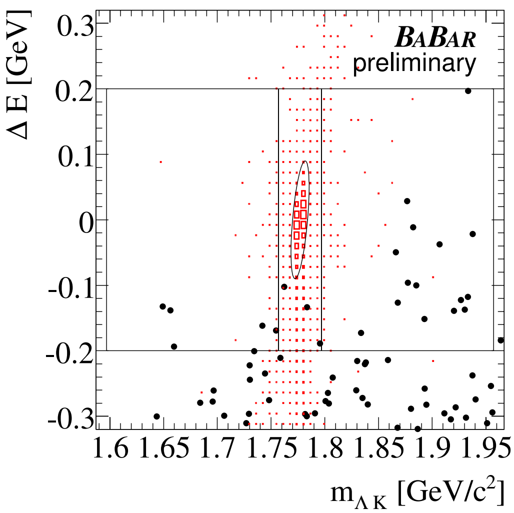
The signal efficiencies have been obtained from Monte Carlo simulations. Systematic uncertainties have been studied using independent control samples of real data. The largest contributions are from uncertainties related to the tracking efficiency and Λ reconstruction. The latter has been estimated by comparing lifetime distributions of long-lived particles in data and Monte Carlo. The uncertainty on the branching fraction $\mathcal{B}(\Lambda \to p\pi^-)$ has been taken from the Review of Particle Physics [2]. Contributions to the systematic uncertainty are added in quadrature to give a total systematic uncertainty of 6.9% for the mode $\tau \to \Lambda\pi$ and 7.0% for $\tau \to \Lambda K$.



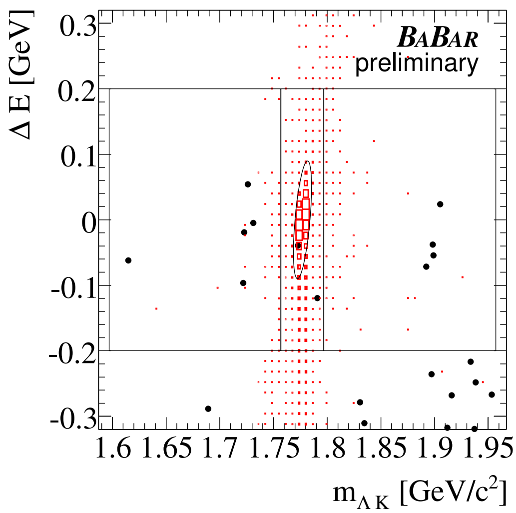
(a) $\tau^- \to \overline{\Lambda}\pi^-$



(b) $\tau^- \to \Lambda\pi^-$



(c) $\tau^- \to \overline{\Lambda}K^-$



(d) $\tau^- \to \Lambda K^-$

Figure 1. $\Delta E_{\Lambda\pi(K)}$ versus $m_{\Lambda\pi(K)}$ distributions for the $(B-L)$-conserving modes (left) and the $(B-L)$-violating modes (right). The top row shows the mode $\tau \to \Lambda\pi$, and the bottom row shows the mode $\tau \to \Lambda K$. The expected signal distributions (taken from Monte Carlo) are shown as the stippled regions (red squares if seen in colour); data events are shown as black dots. The large rectangles in each plot are, from left to right: left sideband, blinded region, and right sideband. The elliptical signal regions are also shown.

Table 1
The number of expected background events in the signal region, signal efficiency, number of observed events, 90% CL upper limit for the signal yield (ℓ), and the upper limit branching fraction for each mode.

mode	$(B-L)$	expected background	efficiency %	observed events	ℓ	upper limit on $\mathcal{B}$ @ 90% CL
$\tau^- \to \overline{\Lambda}\pi^-$	conserving	0.42 ± 0.42	12.28	0	1.97	5.9×10^{-8}
$\tau^- \to \Lambda\pi^-$	violating	0.56 ± 0.56	12.21	0	1.90	5.8×10^{-8}
$\tau^- \to \overline{\Lambda}K^-$	conserving	0.26 ± 0.26	10.63	0	2.08	7.2×10^{-8}
$\tau^- \to \Lambda K^-$	violating	0.12 ± 0.12	9.47	1	3.78	15×10^{-8}

5. RESULTS

The data distributions in the $\Delta E_{\Lambda\pi(K)}$ versus $m_{\Lambda\pi(K)}$ plane after all selection requirements are shown in Figure 1. No signal candidate events are observed in the $\tau \to \Lambda\pi$ mode. We observe one candidate event in the $(B-L)$-violating mode $\tau^- \to \Lambda K^-$. We determine upper limits on branching fractions at 90% CL using the method described in Ref. [17]. This method considers uncertainties both on the signal efficiency as well as the number of expected background events in the signal region. The number of expected background events and number of observed events in the signal region, the signal efficiency, and the upper limit that has been determined are shown in Table 1, separately for the $(B-L)$-violating and $(B-L)$-conserving cases. The upper limit on the branching fraction is given by

$$\mathcal{B}_{UL}(\tau \to \Lambda\pi(K)) = \frac{\ell}{2\sigma_{\tau\tau}\mathcal{L}\mathcal{B}(\Lambda \to p\pi)\varepsilon} \;, \qquad (1)$$

where ℓ is the 90% CL upper limit for the signal yield, $\sigma_{\tau\tau} = 0.89$ nb is the assumed cross section for production of τ pairs, $\mathcal{L} = 237\ \mathrm{fb}^{-1}$ is the total luminosity of our dataset, $\mathcal{B}(\Lambda \to p\pi) = 0.639$ is the Λ branching fraction taken from Ref. [2], and ε is the signal efficiency.

6. SUMMARY

A search for the $(B-L)$-conserving modes $\tau^- \to \overline{\Lambda}\pi^-$ and $\tau^- \to \overline{\Lambda}K^-$ as well as the $(B-L)$-violating modes $\tau^- \to \Lambda\pi^-$ and $\tau^- \to \Lambda K^-$ has been performed using 237 fb^{-1} of e^+e^- data. No signal is observed and we obtain preliminary upper limits on the branching fractions at 90% CL of $\mathcal{B}(\tau^- \to \overline{\Lambda}\pi^-) < 5.9 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \Lambda\pi^-) < 5.8 \times 10^{-8}$, $\mathcal{B}(\tau^- \to \overline{\Lambda}K^-) < 7.2 \times 10^{-8}$, and $\mathcal{B}(\tau^- \to \Lambda K^-) < 15 \times 10^{-8}$. This analysis is the first measurement of the mode $\tau \to \Lambda K$, and it improves over earlier measurements of the mode $\tau \to \Lambda\pi$.

Acknowledgements
The work presented here is that of the entire *BABAR* Collaboration. Special thanks go to Leif Wilden, who did most of the physics analysis and wrote most of the text. I just gave the talk. I would also like to thank the organisers of Tau 2006, and in particular Alberto Lusiani, for what was an excellent workshop.

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