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Measurement of the lifetime of tau-lepton

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Abstract

The lifetime of the τ-lepton is measured using the process $e^+e^- \to \tau^+\tau^-$, where both τ-leptons decay to $3\pi\nu_\tau$. The result for the mean lifetime, based on 711 fb^{-1} of data collected with the Belle detector at the $\Upsilon(4S)$ resonance and 60 MeV below, is $\tau = (290.17 \pm 0.53(\mathrm{stat.}) \pm 0.33(\mathrm{syst.})) \cdot 10^{-15}$ s. The first measurement of the lifetime difference between τ^+ and τ^- is performed. The upper limit on the relative lifetime difference between positive and negative τ-leptons is $|\Delta\tau|/\tau < 7.0 \times 10^{-3}$ at 90% CL.

High precision measurements of the mass, lifetime and leptonic branching fractions of the τ-lepton can be used to test lepton universality [1, 2], which is assumed in the Standard Model. Among the recent experimental results that may manifest the violation of the lepton universality in the case of the τ-lepton, the combined measurement of the ratio of the branching fraction of W-boson decay to $\tau\nu_\tau$ to the mean branching fraction of W-boson decay to $\mu\nu_\mu$ and $e\nu_e$ by the four LEP experiments stands out: $2\mathcal{B}(W \to \tau\nu_\tau)/(\mathcal{B}(W \to \mu\nu_\mu) + \mathcal{B}(W \to e\nu_e)) = 1.066 \pm 0.025$ [3], which differs from unity by 2.6 standard deviations. The present PDG value of the τ-lepton lifetime $(290.6 \pm 1.0) \cdot 10^{-15}$ s [4] is dominated by the results obtained in the LEP experiments [5, 6, 7, 8]. The results of the analysis described below are recently published in [9]. 1

In the following, we use symbols with and without an asterisk for quantities in the e^+e^- center-of-mass (CM) and laboratory frame, respectively. In the CM frame, τ^+ and τ^- leptons emerge back to back with the energy E^*_τ equal to the beam energy E^*_{beam} if we neglect the initial- (ISR) and final-state radiation (FSR). We determine the direction of the τ-lepton momentum in the CM frame as follows. If the neutrino mass is assumed to be zero for the hadronic decay $\tau \to X\nu_\tau$ (X representing the hadronic system with mass m_X and energy E^*_X), the angle θ^* between the momentum $\vec{P}^*_X$ of the hadronic system and that of the τ-lepton is given by:

$$\cos\theta^* = \frac{2E^*_\tau E^*_X - m^2_\tau - m^2_X}{2P^*_X\sqrt{(E^*_\tau)^2 - m^2_\tau}}. \tag{1}$$

The requirement that the τ-leptons be back to back in the CM can be written as a system of three equations: two linear and one quadratic. For the components x^*, y^*, z^* of the unit vector $\hat{n}^*_+$ representing the direction of the positive τ-lepton, we write:

$$\begin{cases} x^* \cdot P^*_{1x} + y^* \cdot P^*_{1y} + z^* \cdot P^*_{1z} = |P^*_1| \cos\theta^*_1 \\ x^* \cdot P^*_{2x} + y^* \cdot P^*_{2y} + z^* \cdot P^*_{2z} = -|P^*_2| \cos\theta^*_2 \\ (x^*)^2 + (y^*)^2 + (z^*)^2 = 1 \end{cases} \tag{2}$$

where $\vec{P}^*_1$ and $\vec{P}^*_2$ are the momenta of the hadronic systems in the CM and $\cos\theta^*_i$ ($i = 1, 2$) are given by Eq. (1). Index 1 (2) is used for the positive (negative) τ-lepton.

There are two solutions for Eq. (2), so the direction $\hat{n}^*_+$ is determined with twofold ambiguity. In the present analysis, we take the mean vector of the two solutions of Eq. (2) as the direction of the τ-lepton in CM. The analysis of MC simulated events shows that there is no bias due to this choice.

Each direction $\hat{n}^*_\pm$ is converted to a four-momentum using the $e^\pm$ beam energy and the τ mass. Both four-momenta are then boosted into the laboratory frame,

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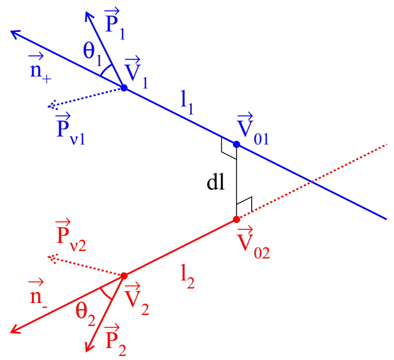

Figure 1: The schematic view of the $\tau^+\tau^-$ event in the laboratory frame.

each passing through the corresponding τ decay vertex $\vec{V}_i$ that is determined by the three pion-daughter tracks (see Fig. 1). We approximate the trajectory of τ-leptons in the magnetic field of the Belle detector with a straight line. Due to the finite detector resolution, these straight lines do not intersect at the $\tau^+\tau^-$ production point. The three-dimensional separation between these lines is characterized by the distance dl between the two points ($\vec{V}_{01}$ and $\vec{V}_{02}$) of closest approach. The typical size of dl is ~ 0.01 cm. For the production point of each τ-lepton, we take the points $\vec{V}_{01}$ and $\vec{V}_{02}$. The flight distance l_1 (l_2) of the τ^+ (τ^-) in the laboratory frame is defined as the distance between the points $\vec{V}_1$ and $\vec{V}_{01}$ ($\vec{V}_2$ and $\vec{V}_{02}$). The proper time t (the product of the speed of light and the decay time of τ-lepton) for the positive τ-lepton is equal to the distance l_1 divided by its relativistic kinematic factor $\beta\gamma$ in the laboratory frame: $t_1 = l_1/(\beta\gamma)_1$. The corresponding parameter for the negative τ-lepton is $t_2 = l_2/(\beta\gamma)_2$.

The analysis presented here is based on the data collected with the Belle detector [10, 11] at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [12, 13] operating at the $\Upsilon(4S)$ resonance and 60 MeV below. The total integrated luminosity of the data sample used in the analysis is 711 fb^{-1}. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector (SVD1) were used for the first sample of 157 fb^{-1}, while a 1.5 cm beampipe, a 4-layer silicon detector (SVD2) and a small-cell inner drift chamber were used to record the remaining 554 fb^{-1} [14].

The following requirements are applied for the selection of the $\tau^+\tau^-$ events where both τ-leptons decay into three charged pions and a neutrino: there are exactly six charged pions with zero net charge and there are no other charged tracks; the thrust value of the event in the CM frame is greater than 0.9; the square of the transverse momentum of the 6π system is required to be greater than 0.25 (GeV/c)^2 to suppress the $e^+e^- \to e^+e^-6\pi$ two-photon events; the mass $M(6\pi)$ of the 6π system should fulfill the requirement 4 GeV/c^2 $< M(6\pi) <$ 10.25 GeV/c^2 to suppress other background events; there should be three pions (triplet) with net charge equal to ± 1 in each hemisphere (separated by the plane perpendicular to the thrust axis in the CM), the pseudomass (see the definition in Ref. [15]) of each triplet of pions must be less than 1.8 GeV/c^2 and each pion-triplet vertex-fit quality must satisfy $\chi^2 < 20$; the discriminant D of Eq. (2) should satisfy $D > -0.05$ (with slightly negative values arising from experimental uncertainties; if this happens, we use $D = 0$ when solving the equation); the distance of closest approach must satisfy $dl < 0.03$ cm to reject events with large uncertainties in the reconstructed momenta and vertex positions. All of these selection criteria are based on a study of the signal and background Monte Carlo (MC) simulated events. For the signal MC sample, we use $\tau^+\tau^-$ events produced by the KKMC generator [16] with the mean lifetime $\langle\tau\rangle = 87.11\,\mu$m that are then fed to the full detector simulation based on GEANT 3 [17]. These events are passed through the same reconstruction procedures as for the data. For the background estimation, we use the MC samples of events generated by the EVTGEN program [18], which correspond to the one-photon annihilation diagram $e^+e^- \to q\bar{q}$, where $q\bar{q}$ are $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ (uds events), $c\bar{c}$ (charm events), and $e^+e^- \to \Upsilon(4S) \to B^+B^-, B^0\bar{B}^0$ (beauty events). All these events are passed through the full detector simulation and reconstruction procedures. The statistics in these MC samples are equivalent to the integrated luminosity of the data, *i.e.,* the number of events of a given category is equal to the product of the integrated luminosity of the data and the expected cross section from theory. For the estimation of the background from the process $\gamma\gamma \to$ *hadrons* ($\gamma\gamma$ events), we use events generated by PYTHIA [19] that are subjected to the aforementioned simulation and reconstruction procedures. In addition to the above MC samples, we also use two $e^+e^- \to \tau^+\tau^-$ MC samples, generated by KKMC, where both τ-leptons are forced to decay into three charged pions and a neutrino. The mean lifetimes for these two samples are 84 and 90 μm, which are about 10σ below and above the PDG value. These two samples are also passed through the same detector simulation and reconstruction procedures.

In the measured proper time distribution, the exponential behavior is smeared by the experimental resolu-