SLAC–PUB–5605
July 1991
(T/E)

# REVIEW OF TAU LEPTON DECAYS

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## ABSTRACT

Measurements of the $\tau$ decay modes are reviewed and compared with the predictions of the Standard Model. While the agreement is generally good, the status of the "1-prong puzzle" remains controversial and a discrepancy between the measured leptonic branching fractions and the $\tau$ lifetime persists. Prospects for precision measurements at a Tau-Charm Factory are also reviewed.

## TAU DECAYS

The $\tau$ lepton was discovered[1] at the SPEAR $e^+e^-$ storage ring in 1975, and was the first observed member of the third generation of fundamental fermions. Recent experiments at SLC and LEP have ruled out the existence of further generations containing fermions with masses below $45\,\mathrm{GeV/c^2}$. The $\tau$ is therefore unlikely to lose it's status as the heaviest known lepton soon. The Standard Model makes definite predictions for the $\tau$ leptonic decay modes and, *via* other experimental data, for some of the hadronic decay modes. If there is new physics, which could well cause larger deviations from Standard Model predictions for the heavier particles, it's effects may become apparent in precise $\tau$ decay measurements.

In the Standard Model the $\tau$ and $\nu_\tau$ are spin 1/2 Dirac particles which couple to the $W$ with a universal (V-A) strength $G_F$. Experimentally, the $\tau$ is found to have spin 1/2 from the energy dependence of the $e^+e^- \to \tau^+\tau^-$ cross section near threshold[2]. The 1990 world average measured masses and $\tau$ lifetime are[3] $m_\tau = 1784.1^{+2.7}_{-3.6}\,\mathrm{MeV/c^2}$, $m_{\nu_\tau} < 35\,\mathrm{MeV/c^2}$, and $\tau_\tau = (0.303 \pm 0.008)\,\mathrm{ps}$.

The leptonic decay rates are given by

$$\Gamma(\tau^- \to \nu_\tau \ell^- \overline{\nu}_\ell) = \frac{G_F^2 m_\tau^5}{192\pi^3}(1 - 8y + 8y^3 - y^4 - 12y^2 \ln y), \qquad y = m_\ell^2/m_\tau^2$$

where $\ell = e, \mu$; the neutrinos are assumed massless, and W mass and radiative corrections are ignored. The leptonic branching fractions are predicted from the measured muon and tau lifetimes and masses to be $B_e = (\tau_\tau/\tau_\mu)(m_\tau/m_\mu)^5 = (18.9 \pm 0.5)\%$, and $B_\mu = 0.973 B_e = (18.4 \pm 0.5)\%$. The 1990 world average experimental values $B_e = (17.7 \pm 0.4)\%$ and $B_\mu = (17.8 \pm 0.4)\%$ are $2.0\sigma$ lower than the above predictions. Alternatively, one may use the experimental $B_e' = (B_e + B_\mu)/1.973 = (18.0 \pm 0.3)\%$ to obtain the prediction $\tau_\tau = B_e' \tau_\mu (m_\mu/m_\tau)^5 = (0.288 \pm 0.005)\,\mathrm{ps}$.

*Invited talk given at 4th Conference on The Intersections Between Particle and Nuclear Physics, Tuczon, AZ, May 24–29, 1991*

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⋆ Work supported by the Department of Energy, contract DE–AC03–76SF00515.

The leptonic branching fractions yield $R_H \equiv B(\tau^- \to \nu_\tau + hadrons)/B'_e = 3.58 \pm 0.09$ while the lifetime measurement predicts $R_H = 3.32 \pm 0.14$. Pich[4] has found $R_H$ may be predicted accurately from QCD because the non-perturbative corrections are small. The result is sensitive to the QCD-scale $\Lambda_{\overline{MS}}$ with $R_H = 3.29 \pm 0.02$ for $\Lambda_{\overline{MS}} = 100\,\mathrm{MeV}$, and $R_H = 3.52 \pm 0.02$ for $\Lambda_{\overline{MS}} = 300\,\mathrm{MeV}$. Hadronic $\tau$ decays also provide a means of testing other aspects of low-energy QCD such as chiral symmetry, vacuum condensates, and resonance structures free from other final state interactions.

Tsai[5] has given the hadronic decay rate of the $\tau$ in terms of vector and axial-vector spectral functions corresponding to the allowed hadronic final states with $J^P = (0^-, 1^-, 1^+)$ for strangeness $S = 0$ and $J^P = (0^-, 0^+, 1^-, 1^+)$ for $S = -1$. The $(J^P = 0^+, S = 0)$ final state is forbidden by CVC while PCAC allows only $\tau^- \to \pi^-\nu_\tau$ for the $(J^P = 0^-, S = 0)$ final state. The first class vector and axial-vector weak currents have G-parity G= +1 and −1 respectively, while the corresponding second class currents have G= −1 and +1. Hadronic final states occuring through second class currents, such as $\pi^-\eta$, therefore have $GP(-1)^J < 0$. In the Standard Model second class currents arise from electromagnetic corrections to the strong interaction isospin symmetry and should be suppressed by a factor $\sim 10^{-4}$, and are at present unobserved.

While the individual hadronic decay rates cannot be calculated directly from QCD, it is often possible to relate them to other experimental data. The non-strange spin-1 vector current is related by CVC to the isovector part of the $e^+e^- \to$ *hadrons* cross section. Examples of such $J^P = 1^-$ final states are $\rho$, $\pi^-\pi^-\pi^+\pi^0$, and $\pi^-3\pi^0$. No similar relation exists for the axial-vector current, for which the possible final states include those with odd numbers of pions. However, the $\pi^-$ and $K^-$ coupling strengths to the axial-vector current in $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to K^-\nu_\tau$ are known from the decays $\pi^- \to \mu^-\overline{\nu}_\mu$ and $K^- \to \mu^-\overline{\nu}_\mu$. The 1990 world average branching fractions shown in Table 1 are in good agreement with the theoretical predictions of Gilman and Rhie[6], and Kühn and Santamaria[7]. Radiative corrections[8] to the predictions are not included in Table 1. One expects $B(\tau^- \to \pi^-2\pi^0\nu) = B(\tau^- \to 2\pi^-\pi^+\nu)$ if the decays occur exclusively through the $a_1$. Table 1 also shows the topological branching fractions where "n-prong" denotes the number of charged particles in the decay.

A long-standing problem in $\tau$ decays has been the "1-prong puzzle". According to the 1990 Particle Data Book[3] the measured inclusive 1-prong branching fraction exceeds the sum of the exclusive 1-prong modes by $(5.8 \pm 1.4)\%$. The sum uses theoretical limits for unmeasured or poorly measured exclusive modes. Sources of the discrepancy may be errors in the experimental measurements or theoretical limits, or unexpected decay modes not included in the sum. The world averages are obtained assuming uncorrelated errors. However, Hayes and Perl[9] found better than expected agreement between measurements, indicating

| Decay Mode | $B_i$ (%) | $R_i = B_i/B_e$ | $R_i$ (theory) |
|---|---|---|---|
| $\tau^- \rightarrow e^-\nu\overline{\nu}$ | $17.7 \pm 0.4$ | | |
| $\tau^- \rightarrow \mu^-\nu\overline{\nu}$ | $17.8 \pm 0.4$ | $1.006 \pm 0.032$ | $0.973$ |
| $\tau^- \rightarrow \pi^-\nu$ | $11.0 \pm 0.5$ | $0.62 \pm 0.03$ | $0.607$ |
| $\tau^- \rightarrow K^-\nu$ | $0.68 \pm 0.19$ | $0.038 \pm 0.011$ | $0.040 \pm 0.002$ |
| $\tau^- \rightarrow K^{*-}\nu$ | $1.39^{+0.18}_{-0.20}$ | $0.079 \pm 0.011$ | $0.064$ |
| $\tau^- \rightarrow \rho^-\nu$ | $22.7 \pm 0.8$ | $1.28 \pm 0.05$ | $1.32 \pm 0.05$ |
| $\tau^- \rightarrow \pi^-2\pi^0\nu$ | $7.5 \pm 0.9$ | $0.42 \pm 0.05$ | $\leq x$ |
| $\tau^- \rightarrow \pi^-3\pi^0\nu$ | $3.0 \pm 2.7$ | $0.17 \pm 0.15$ | $0.055 \pm 0.005$ |
| $\tau^- \rightarrow 2\pi^-\pi^+\nu$ | $7.1 \pm 0.6$ | $0.40 \pm 0.03$ | $x$ |
| $\tau^- \rightarrow 2\pi^-\pi^+\pi^0\nu$ | $4.4 \pm 1.6$ | $0.25 \pm 0.09$ | $0.275^{+0.03}_{-0.09}$ |
| $\tau^- \rightarrow 3\pi^-2\pi^+\nu$ | $0.056 \pm 0.016$ | $0.003 \pm 0.001$ | |
| $\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$ | $0.051 \pm 0.022$ | $0.003 \pm 0.001$ | |
| 1-prong | $86.13 \pm 0.33$ | | |
| 3-prong | $13.76 \pm 0.32$ | | |
| 5-prong | $0.113 \pm 0.027$ | | |

Table 1. 1990 world average branching fractions.

correlated or over-estimated systematic errors, or measurement bias. Furthermore, when only statistical errors were used the $\tau^- \rightarrow \rho^-\nu_\tau$ measurements still appeared overly consistent.

The CELLO Collaboration has proposed[10] a solution to the 1-prong puzzle which has been discussed in detail by Kiesling[11]. First, their measurement of the inclusive 1-prong branching fraction $B_1 = (84.9 \pm 0.4 \pm 0.3)\%$ is less than the 1990 world average (Table 1). Second, since known decay modes account for $(99.8 \pm 2.6 \pm 1.2)\%$ of their events, they find no evidence for unexpected decay modes. Third, their measurements of the exclusive 1-prong modes $B(\tau^- \rightarrow e^-\nu\overline{\nu}) = (18.4 \pm 0.8 \pm 0.4)\%$ and $B(\tau^- \rightarrow \pi^-2\pi^0\nu) = (10.0 \pm 1.5 \pm 1.1)\%$ are larger than the 1990 world average values of $(17.7 \pm 0.4)\%$ and $(7.5 \pm 0.9)\%$ respectively.

New measurements presented at the 1991 Heavy Flavors Conference (Orsay, 24-29 June) are summarized in Table 2. They are preliminary except for those of ALEPH and OPAL. Other recent measurements are $B(\tau^- \rightarrow h^-\pi^0\nu) = (22.0 \pm 0.8 \pm 1.9)\%$ and $B(\tau^- \rightarrow h^-2\pi^0\nu) = (5.7 \pm 0.5^{+1.7}_{-1.0})\%$ by the Crystal Ball[12] ($h = hadron$); $B(\tau^- \rightarrow h^-2\pi^0\nu) = (0.367 \pm 0.031)B(\tau^- \rightarrow h^-\pi^0\nu)$ and $B(\tau^- \rightarrow h^-3\pi^0\nu) = (0.033 \pm 0.011)B(\tau^- \rightarrow h^-\pi^0\nu)$ by CLEO[13]; and $\tau_\tau = (0.310 \pm 0.015 \pm 0.010)$ ps by CLEO[14]. ALEPH finds the sum of exclusive 1-prong modes to be in excellent agreement with the topological 1-prong branching fraction, whereas ARGUS finds a $> 2.5\sigma$ deficit. The ALEPH measurement of $B(\tau^- \rightarrow (3\pi^\pm)^-\nu)$

| | $\tau^- \to e^-\nu\bar{\nu}$ | $\tau^- \to \mu^-\nu\bar{\nu}$ | $\tau^- \to h^-\nu$ |
|---|---|---|---|
| ALEPH | $18.0 \pm 0.5 \pm 0.4$ | $17.3 \pm 0.4 \pm 0.3$ | $13.3 \pm 0.4 \pm 0.3$ |
| ARGUS | $17.6 \pm 0.4 \pm 0.4$ | $17.0 \pm 0.4 \pm 0.5$ | $11.2 \pm 0.6 \pm 0.7$ |
| CLEO | $19.0 \pm 0.4 \pm 0.7$ | | |
| L3 | $17.7 \pm 0.7 \pm 0.6$ | $17.5 \pm 0.8 \pm 0.5$ | |
| OPAL | $17.4 \pm 0.5 \pm 0.4$ | $16.8 \pm 0.5 \pm 0.4$ | $12.1 \pm 0.7 \pm 0.5$ |
| | $\tau^- \to \rho^-\nu$ | $\tau^- \to \pi^-2\pi^0\nu$ | $\tau^- \to \pi^-3\pi^0\nu$ |
| ALEPH | $24.5 \pm 0.6 \pm 0.8$ | $10.2 \pm 0.7 \pm 0.8$ | $1.4 \pm 0.4 \pm 0.5$ |
| ARGUS | $22.3 \pm 0.4 \pm 0.9$ | | |
| Crystal Ball | $22.9 \pm 0.8 \pm 1.6$ | | |
| | $\tau^- \to (3\pi^\pm)^-\nu$ | $\tau^- \to (3\pi^\pm)^-\pi^0\nu$ | $\tau^- \to (3\pi^\pm)^-(\geq 1\pi^0)\nu$ |
| ALEPH | $9.5 \pm 0.4 \pm 0.6$ | | $4.9 \pm 0.3 \pm 0.7$ |
| ARGUS | $7.1 \pm 0.1 \pm 0.5$ | $5.4 \pm 0.4 \pm 0.5$ | |
| | 1-prong | 3-prong | 5-prong |
| ALEPH | $85.5 \pm 0.4 \pm 0.1$ | $14.4 \pm 0.4 \pm 0.1$ | $0.10^{+0.05}_{-0.04} \pm 0.03$ |
| ARGUS | $86.6 \pm 0.3 \pm 0.6$ | $13.3 \pm 0.3 \pm 0.6$ | |
| L3 | $85.6 \pm 0.6 \pm 0.3$ | $14.4 \pm 0.6 \pm 0.3$ | $< 0.3\%$ (95% CL) |
| | Lifetime (ps) | | |
| DELPHI | $0.314 \pm 0.023 \pm 0.008$ | | |
| L3 | $0.309 \pm 0.023 \pm 0.030$ | | |
| OPAL | $0.313 \pm 0.011 \pm 0.013$ | | |

Table 2. New branching fractions (%) and lifetimes (Orsay, June 1991).

is significantly larger than the ARGUS result. Also, the recent CLEO and Crystal Ball measurements of $B(\tau^- \to h^-2\pi^0\nu)$ are considerably less than the CELLO and ALEPH measurements. The 1-prong puzzle therefore remains controversial.

The new $\tau$ lifetime measurements are remarkably consistent and are all larger than the 1990 world average. The averages of the new $B(\tau^- \to e^-\nu\bar{\nu})$ and $B(\tau^- \to \mu^-\nu\bar{\nu})$ measurements are larger and smaller respectively than the 1990 world averages. Overall this somewhat worsens the discrepancy between the lifetime and leptonic branching fractions.

ARGUS has published a precise measurement of the Michel parameter in the leptonic decays[15], $\rho = 0.742 \pm 0.035$, and the first measurement[16] of the $\nu_\tau$ helicity, $h_{\nu_\tau} = -1.14 \pm 0.34^{+0.34}_{-0.17}$. The measurements are consistent with the $(V-A)$ values $\rho = 3/4$ and $h_{\nu_\tau} = -1$, but do not require a $(V-A)$ interaction.

## PHYSICS PROSPECTS AT A TAU-CHARM FACTORY

Significant progress in $\tau$ physics will require reduced backgrounds and systematic errors as well as higher statistics. The best way to achieve this in a dedicated experiment running at high luminosity near the $e^+e^- \to \tau^+\tau^-$ threshold, such as at a Tau-Charm Factory[17] which may be built soon in Spain.

A Tau-Charm Factory would have three main advantages over other experiments. First, backgrounds are greatly reduced by running just above the $\tau$-pair threshold and below the open charm threshold. Second, the backgrounds may be measured directly by running just below the $\tau$-pair threshold, and systematic measurement errors may be minimized by frequent short runs at the $J/\psi$ where the high signal rate ($\simeq 1\,\text{kHz}$) may be used to calibrate and monitor detector performance. Third, with a design luminosity of $\mathcal{L} = 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ in the $3-5\,\text{GeV}$ energy range, production of $> 10^7$ $\tau$-pairs per year is possible.

Voloshin[18] has shown that the Coulomb attraction between the $\tau^+\tau^-$ pair leads to a production cross section $\sigma_{\tau\tau} = 0.23\,\text{nb}$ at threshold. For comparison, $\sigma_{\tau\tau}$ is 2.4 nb at 3.67 GeV (just below the $\psi'$) and attains a maximum of 3.5 nb at 4.25 GeV. Running at threshold yields kinematically separated $\pi$ and $K$ decay modes which are essentially monochromatic. This allows $\tau^+\tau^-$ events to be single-tagged by the monochromatic $\pi$ plus missing energy. The single-tags $(e^\pm + E_{miss})$ and $(\mu^\pm + E_{miss})$ with $E_{miss} \geq 0.8\,\text{GeV}$ may also be used. Monte Carlo studies have shown that $\tau^+\tau^-$ events may be identified by the $(e^\pm + E_{miss})$ single-tag with 24% efficiency while suppressing the hadronic background fraction to 0.12% at threshold and to 0.02% at 3.67 GeV.

Near threshold the maximum particle momentum of about 1 GeV/c permits time-of-flight and dE/dx techniques to discriminate between $\pi^\pm$, $K^\pm$, and $p$. In addition, the near isotropy of the decay products minimizes the detection inefficiency due to charged and neutral pile-up which is a particular problem in measuring the multi-$\pi^0$ decay modes at higher energy machines.

Running for 1 year at $\mathcal{L} = 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ should allow measurement of the decays $\tau^- \to e^-\nu\bar{\nu}$, $\mu^-\nu\bar{\nu}$, and $\pi^-\nu$ to relative precisions of $\leq 0.2\%$, and $\tau^- \to K^-\nu$ to 0.8% precision. Since these decays are understood at the level of electroweak radiative corrections (1%) such precise measurements could provide sensitivity to new physics beyond the Standard Model. In searches for rare or forbidden decays the Tau-Charm Factory could ultimately set upper limits as low as $\simeq 10^{-8}$.

A precise measurement of the $e^+e^- \to \tau^+\tau^-$ cross section near threshold at the Tau-Charm factory should determine the $\tau$ mass with an accuracy of $0.1\,\text{MeV/c}^2$. This requires calibration of the beam energy to an absolute accuracy of about $10^{-5}$ using the resonance depolarization technique[19].

If the $\nu_\tau$ is massless the Tau-Charm Factory could set an upper limit (95% CL) of $3\,\text{MeV/c}^2$ from $20\,\text{fb}^{-1}$ (2 years) of data at 3.67 GeV by measuring the endpoints of the $3\pi^-2\pi^+$ and $K^-K^+\pi^-$ mass spectra in $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \rightarrow K^-K^+\pi^-\nu_\tau$. Contamination from $e^+e^- \rightarrow$ *hadrons* can be measured directly just below the $\tau$-pair threshold. The $\pi^\pm$ and $K^\pm$ momentum measurements can be calibrated directly using $D^- \rightarrow 3\pi^-2\pi^+$ at the $\psi'$.

Fetscher[20] has shown that the Lorentz structure of the charged weak interaction in the decays $\tau^- \rightarrow e^-\nu_\tau\overline{\nu}_e$ and $\tau^- \rightarrow \mu^-\nu_\tau\overline{\nu}_\mu$ can be completely determined by measurements of the $\tau$ lifetime, the asymmetry parameters $\xi$ and $\delta$, the $e^-$ or $\mu^-$ polarization $\xi'$ and the rate for inverse $\tau$ decay $\nu_\tau + e^- \rightarrow \tau^- + \nu_e$. The Tau-Charm Factory should be able to measure $\xi$ and $\delta$ to an accuracy of 1%, and $\xi'_\mu$ to 10% by means of a muon polarimeter. In addition, the decay paramters $\rho$ and $\eta$ could be measured with accuracies of 0.3% and 1% respectively.

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