τ BRANCHING FRACTIONS

Revised April 1998 by K.G. Hayes (Hillsdale College).

For the last six years, the rate of publication of new experimental results on the τ lepton has been high. The 30 new experimental papers listed in the τ References for this edition have produced significant changes in the τ Listings. The new results are made possible by the large τ data sets accumulated by the LEP experiments and by CLEO. Measurements of new τ-decay modes with small ($< 10^{-3}$) branching fractions have been published, and stringent upper limits on other new allowed τ decays have also been published. Significant improvements in branching fraction upper limits for forbidden τ decays have been made including the determination of upper limits for 12 new forbidden decay modes. The great majority of branching fraction upper limits for forbidden modes are now in the range of 10^{-5} to 10^{-6}.

Relatively precise branching fractions for 3-prong exclusive τ-decay modes containing charged kaons have finally been published [1]. This allows the determination of branching fractions for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$, the last exclusive τ-decay modes with large branching fractions to be measured. The new measurements have resulted in a 30% increase in the number of τ-decay modes in the Listings; 176 decay modes are listed in the current edition, although many are not mutually independent.

There have also been many new measurements of τ-decay parameters. For most parameters, the uncertainty on the world average has decreased by a factor of 2.5 or more. Finally, new experimental limits have been published for the various τ-dipole moments. However, there have been few new measurements of τ-decay modes with large branching fractions, and the world average values for most of these branching fractions have changed little since the last edition.

The constrained fit to τ branching fractions: The Lepton Summary Table and the List of τ-Decay Modes contain branching fractions for 105 conventional τ-decay modes and upper limits on the branching fractions for 22 other conventional

τ-decay modes. Of the 105 modes with branching fractions, 76 are derived from a constrained fit to τ branching fraction data. The goal of the constrained fit is to make optimal use of the experimental data to determine τ branching fractions. For example, the new branching fractions for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ are determined mostly from experimental measurements of the branching fractions for modes $\tau^- \to h^-h^-h^+\nu_\tau$ and $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ and the new measurements of exclusive branching fractions for 3-prong modes containing charged kaons and 0 or 1 π^0's.

Branching fractions from the constrained fit are derived from a set of basis modes. The basis modes form an exclusive set whose branching fractions are constrained to sum exactly to one. The list of 29 basis modes selected for the 1998 fit are listed in Table 1. The only change for the 1996 basis set is that the two modes $\tau \to h^-h^-h^+\nu_\tau$ (ex. K^0,ω) and $\tau \to h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0,ω) have been replaced by the six new modes:

$\tau \to \pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0,ω),
$\tau \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0,ω),
$\tau \to K^-\pi^+\pi^-\nu_\tau$ (ex. K^0),
$\tau \to K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0),
$\tau \to K^-K^+\pi^-\nu_\tau$, and
$\tau \to K^-K^+\pi^-\pi^0\nu_\tau$.

In selecting the basis modes, assumptions and choices must be made. Factors pertaining to the selection of the 1996 basis modes are described in the 1996 edition. Additional assumptions have been made in selecting the six new modes for the 1998 basis set. We assume the decays $\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau$ and $\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu_\tau$ have negligible branching fractions. This is consistent with Standard Model predictions for τ decay, although the experimental limits for these branching fractions are not very stringent. The 95% CL upper limits for these branching fractions in the current Listings are $B(\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau) < 0.25\%$ and $B(\pi^+K^-K^- \geq 0\pi^0\nu_\tau) < 0.09\%$, values not so different from measured branching fractions for allowed 3-prong modes containing charged kaons. Although our usual goal is to impose

Table 1: Basis modes for the 1998 fit to τ branching fraction data.

$e^-\overline{\nu}_e\nu_\tau$	$K^-K^0\nu_\tau$
$\mu^-\overline{\nu}_\mu\nu_\tau$	$K^-K^0\pi^0\nu_\tau$
$\pi^-\nu_\tau$	$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0,ω)
$\pi^-\pi^0\nu_\tau$	$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0,ω)
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	$K^-\pi^+\pi^-\nu_\tau$ (ex. K^0)
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0)
$h^-4\pi^0\nu_\tau$ (ex. K^0)	$K^-K^+\pi^-\nu_\tau$
$K^-\nu_\tau$	$K^-K^+\pi^-\pi^0\nu_\tau$
$K^-\pi^0\nu_\tau$	$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0,ω,η)
$K^-2\pi^0\nu_\tau$ (ex. K^0)	$h^-h^-h^+\geq 3\pi^0\nu_\tau$
$K^-3\pi^0\nu_\tau$ (ex. K^0)	$3h^-2h^+\nu_\tau$ (ex. K^0)
$\pi^-\overline{K}^0\nu_\tau$	$3h^-2h^+\pi^0\nu_\tau$ (ex. K^0)
$\pi^-\overline{K}^0\pi^0\nu_\tau$	$h^-\omega\nu_\tau$
$\pi^-K^0\overline{K}^0\nu_\tau$	$h^-\omega\pi^0\nu_\tau$
	$\pi^-\eta\pi^0\nu_\tau$

as few theoretical constraints as possible so that the world averages and fit results can be used to test the theoretical constraints (*i.e.*, we do not make use of the theoretical constraint from lepton universality on the ratio of the τ-leptonic branching fractions $\mathrm{B}(\tau^-\to\mu^-\overline{\nu}_\mu\nu_\tau)/\mathrm{B}(\tau^-\to e^-\overline{\nu}_e\nu_\tau) = 0.9728$), the experimental challenge to identify charged prongs in 3-prong τ decays is sufficiently difficult that experimenters have been forced to make these assumptions when measuring the branching fractions of the allowed decays.

We also assume the branching fraction for the allowed decay $\tau^-\to K^-K^+K^-\geq 0\pi^0\nu_\tau$ is negligible. This decay has limited phase space, and the branching fraction is expected to be very small. The branching fraction upper limit for this decay in the current Listings is $\mathrm{B}(\tau^-\to K^-K^+K^-\geq 0\pi^0\nu_\tau) < 0.21\%$ at 95% CL, and the ALEPH Collaboration [1] has determined a much more stringent limit on the branching fraction $\mathrm{B}(\tau^-\to K^-K^+K^-\nu_\tau) < 0.019\%$ at 90% CL.

Recent measurements of several new decay modes having very small branching fractions have raised two other issues regarding the choice of basis modes. The ALEPH Collaboration has recently measured new branching fractions for 1-prong τ decays containing two neutral kaons [2]. The basis set has just one τ-decay mode containing two neutral kaons: $\tau^- \to \pi^- K^0 \overline{K}^0 \nu_\tau$. In calculating the contribution of this decay to other measured τ-decay modes, we assume the two neutral kaons decay independently:

$$\begin{aligned}\mathrm{B}(\tau^- \to \pi^- K^0_S K^0_S \nu_\tau) &= \mathrm{B}(\tau^- \to \pi^- K^0_L K^0_L \nu_\tau) \\ &= \tfrac{1}{4}\mathrm{B}(\pi^- K^0 \overline{K}^0 \nu_\tau). \\ \mathrm{B}(\tau^- \to \pi^- K^0_S K^0_L \nu_\tau) &= \tfrac{1}{2}\mathrm{B}(\pi^- K^0 \overline{K}^0 \nu_\tau).\end{aligned}$$

This assumption may be incorrect. For example, Bose-Einstein correlations between the two neutral kaons can in principle alter these branching fractions. The ratio of the ALEPH measurement of B $(\tau^- \to \pi^- K^0_S K^0_L \nu_\tau) = (0.101 \pm 0.023 \pm 0.013)\%$ to the average of the CLEO [3] and ALEPH [2] measurements of $\mathrm{B}(\tau^- \to \pi^- K^0_S K^0_S \nu_\tau) = (0.024 \pm 0.005)\%$ is not inconsistent with our assumed value for this ratio of 2. For the sake of simplicity, we retain in this edition the assumption of independent K^0 decay.

There are several newly measured modes with small branching fractions [4] which cannot be expressed in terms of the selected basis modes and are therefore left out of the fit:

$\mathrm{B}(K^0 h^+ h^- h^- \nu_\tau) = (2.3 \pm 2.0) \times 10^{-4}$,
$\mathrm{B}(\pi^- K^0_S K^0_L \pi^0 \nu_\tau) = (3.1 \pm 1.2) \times 10^{-4}$,
$\mathrm{B}(\tau^- \to \pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau) = (6 \pm 4) \times 10^{-4}$,

plus the $\eta \to \gamma\gamma$ component of the branching fractions

$\mathrm{B}(\eta \pi^- \pi^+ \pi^- \nu_\tau) = (3.4 \pm 0.8) \times 10^{-4}$,
$\mathrm{B}(\eta \pi^- \pi^0 \pi^0 \nu_\tau) = (1.4 \pm 0.7) \times 10^{-4}$, and
$\mathrm{B}(\eta K^- \nu_\tau) = (2.7 \pm 0.6) \times 10^{-4}$.

The sum of these excluded branching fractions is $(0.15 \pm 0.05)\%$. This is near our goal of 0.1% for the internal consistency of the τ Listings for this edition, and thus for simplicity we do not include these small branching fraction decay modes in the basis set.

The only significant difference between the world average value and the constrained fit value for branching fractions in the 1996 edition was for the 1-prong and 3-prong topological branching fractions. The average values for the topological branching fractions were dominated by old measurements from the pre-LEP era. Some of these old experiments had significantly underestimated their experimental uncertainties, with the result that, in the period between 1986 and 1990, the uncertainty in the world averages for the 1-prong and 3-prong topological branching fractions were considerably smaller than the uncertainty in the world averages of the very well-measured leptonic branching fractions [5]. Also, several of these old topological branching fraction measurements made the largest contributions the the constrained χ^2 fit. These measurement are now very old and have been retired.

The constrained fit has a χ^2 of 94 for 113 degrees of freedom. The only basis mode branching fraction which shifted more than 1σ from its 1996 value is $\mathrm{B}(\tau^- \to \pi^-\nu_\tau)$ which changed from $(11.31 \pm 0.15)\%$ to $(11.08 \pm 0.11)\%$ due mainly to the new measurement of $\mathrm{B}(\tau^- \to h^-\nu_\tau)$ by the CLEO Collaboration [6]. The fit and average values for the topological branching fractions are consistent. Table 2 compares the current fit and average values for

$\mathrm{B}_1 \equiv \mathrm{B}(\text{particle}^- \geq 0 \text{ neutrals } \geq 0 K_L^0 \nu_\tau)$ and

$\mathrm{B}_3 \equiv \mathrm{B}(h^-h^-h^+ \geq 0 \text{ neutrals } \nu_\tau)$

with the values from the 1996 edition.

Table 2: Fit and average values for B_1 and B_3.

Branching fraction		1996 Fit	1998 Fit
B_1	Fit:	84.96 ± 0.17	84.71 ± 0.13
B_1	Ave:	85.91 ± 0.30	85.1 ± 0.4
B_3	Fit:	14.92 ± 0.17	15.18 ± 0.13
B_3	Ave:	14.01 ± 0.29	14.8 ± 0.4

Another measure of the overall consistency of the τ branching fraction data with the fit constraint is a comparison of the fit and average values for the leptonic branching fractions. Table 3 compares the current fit and average values for $\mathrm{B}_e \equiv \mathrm{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ and $\mathrm{B}_\mu \equiv \mathrm{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$ with the values from the 1996 edition.

Table 3: Fit and average values for $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$.

Branching fraction		1996 Fit	1998 Fit
B_e	Fit:	17.83 ± 0.08	17.81 ± 0.07
B_e	Ave:	17.80 ± 0.08	17.78 ± 0.08
B_μ	Fit:	17.35 ± 0.10	17.37 ± 0.09
B_μ	Ave:	17.30 ± 0.10	17.32 ± 0.09

Conclusions: Many new measurements of τ-lepton properties have been made in the last two years. Experimenters have exploited the availability of large data sets to measure τ-decay modes with either small branching fractions or low detection efficiencies. Charged particle identification in 3-prong decays has finally allowed the experimental determination of the branching fraction for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$, the last exclusive τ-decay modes with large branching fractions to be measured. The basis set of τ-decay modes used in the constrained fit to branching fractions has been expanded to include the new measurements of exclusive 3-prong decays with identified charged prongs and 0 or 1 π^0's. There is no significant evidence of any inconsistency in the branching fraction data used in the constrained fit or to calculate world average values.

References

1. ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. **C1**, 65 (1998).
2. ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. (to be published), CERN-PPE/97-167.
3. CLEO Collaboration, T.E. Coan *et al.*, Phys. Rev. **D53**, 6037 (1996).
4. See the τ Listings for references.
5. K.G. Hayes, Nucl. Phys. Proc. Suppl. **55C**, 23 (1997).
6. CLEO Collaboration, A. Anastassov *et al.*, Phys. Rev. **D55**, 2559 (1997).