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The One Charged Particle Decay Modes of the Tau*

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I. Introduction

Most readers have heard that we do not understand tau lepton decays to modes with one charged particle. As Gilman[1] and Truong[2] emphasized, we cannot completely explain the measured total branching fraction into those modes, B_1. There appears to be a discrepancy between B_1 and the sum of the individual branching fraction measurements, $\sum_i B_{1i}$, when the latter are supplemented with calculations based on conventional theory such as strong isospin conservation. In this paper I discuss some experimental aspects of this subject.

Tables of measurements of B_1 and the major individual branching fractions are given in Sec. II. These tables are taken from a new review by Gan and myself.[3] In Sec. III, I briefly describe why a combination of measurements and calculations is needed to display the discrepancy; uncertainties in measurements of the branching fractions for multiple photon decay modes prevent complete reliance on experiment. The multiple photon modes are discussed in more detail in Sec. IV. I conclude, Sec. V, with a summary of present research of my colleagues and myself on experimental technique problems relative to the apparent discrepancy.

II. Summary of Measurements and Averages

Tables 1–5 list measurements of B_1 and of the major 1-charged particle modes.

$$B_e : \tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \tag{1a}$$

$$B_\mu : \tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{1b}$$

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$$B_\pi : \tau^- \rightarrow \nu_\tau + \pi^- \tag{1c}$$

$$B_\rho : \tau^- \rightarrow \nu_\tau + \rho^- \tag{1d}$$

$$B_{\pi 2\pi^\circ} : \tau^- \rightarrow \nu_\tau + \pi^- + \pi^\circ + \pi^\circ \tag{1e}$$

I have excluded measurements in Tables 1–4 which have very small relative weights. Complete tables are being published by Hayes and I.[4]

The combined error, σ_n, for a measurement n is either given by the authors or is calculated as the sum in quadrature of the statistical and systematic errors. The formal average, y, is obtained from the individual measurements, y_n, via

$$y = \frac{\sum_{n=1}^{N} \left(\frac{y_n}{\sigma_n^2}\right)}{\sum_{n=1}^{N} \left(\frac{1}{\sigma_n^2}\right)} \quad , \tag{2}$$

for a set of N measurements. The formal error is

$$\sigma = \left[\sum_{n=1}^{N} \left(\frac{1}{\sigma_n^2}\right)\right]^{-1/2} \quad . \tag{3}$$

This is the method used by the Particle Data Group,[6] and is discussed in Refs. 4 and 5.

Similar average values for these branching ratios and their errors have been given by Bartish and Stroynouski.[7]

The 1-charged particle decay modes containing a K

$$B_K : \begin{cases} \tau^- \rightarrow \nu_\tau + K^- & , \\ \tau^- \rightarrow \nu_\tau + K^*(890)^- \rightarrow \nu_\tau + K^- + \pi^\circ \ , \end{cases} \tag{4}$$

have small branching ratios. I combine them yielding[3]

$$B_K = 2.2 \pm 0.4\% . \tag{5}$$

I define

$$B_{e\mu\pi\rho K} = B_e + B_\mu + B_\pi + B_\rho + B_K . \tag{6}$$

The experimental signature

$$\tau^- \to x^- + m\gamma + \text{ missing energy}, \quad m > 2 \quad , \tag{7}$$

with $x^- = \pi^-$ or K^-, includes the mode

$$\tau^- \to \nu_\tau + \pi^- + \pi^\circ + \pi^\circ \quad , \tag{1e}$$

already listed in Eq. (1), plus many other modes:

$$\tau^- \to \nu_\tau + x^- + n\pi^\circ, \quad , \quad n \geq 3 \ , \tag{8a}$$

$$\tau^- \to \nu_\tau + x^- + \eta + n\pi^\circ, \quad , \quad n \geq 1 \ , \tag{8b}$$

$$\tau^- \to \nu_\tau + x^- + 2\eta + n\pi^\circ, \quad , \quad n \geq 0 \ . \tag{8c}$$

The η contributes to 1-charged particle modes through $\eta \to 2\gamma$ and $\eta \to 3\pi^\circ$. The x^- in Eqs. (7) and (8) will usually be a π^-.

I exclude from inclusion in the signature in Eq. (7) the controversial mode $\tau^- \to \nu_\tau + \pi^- + \eta$ because the weight of experimental evidence[3] sets an upper limit of 1% or less; indeed, at this meeting Lowe[8] gave a limit of 0.3%. I also exclude modes containing unknown particles.[3,5]

I define $B_{1\,\mathrm{mult\,neut}}$ to be the sum of the branching fractions for the modes in Eq. (1e) and Eqs. (8). Table 5 shows that measurements of $B_{1\,\mathrm{mult\,neut}}$ are poor, the reasons are given by example in Sec. IV. Only $B_{\pi 2\pi^\circ}$ is well measured, and even here there are some questions

(see Sec. IV). Defining

$$B_{1\,\mathrm{mult\,neut} \neq 2\pi^\circ} = B_{1\,\mathrm{mult\,neut}} - B_{\pi 2\pi^\circ} \quad , \tag{9}$$

and using Table 5

$$B_{1\,\mathrm{mult\,neut} \neq 2\pi^\circ}(\mathrm{measured}) \leq 10\% \quad . \tag{10}$$

The number in Eq. (10) is based purely on experimental results. There are measured upper limits on some modes in Eq. (8): $B_{\pi 3\pi^\circ}$ upper limits can be derived from Table 5 and limits exist[8,10] for other modes such as $B_{\pi\eta}$ and $B_{\pi 2\eta}$, but there is no experimental value or limit for all the modes in Eqs. (8).

Table 6 summarizes the experimental situation and gives the partial sums $B_{e\mu\pi\rho K}$ and $B_{e\mu\pi\rho K} + B_{\pi 2\pi^\circ}$.

III. Comparison of B_1 and $\sum_i B_{1i}$

A purely experimental comparison of B_1 and $\sum_i B_{1i}$, Table 7, shows no discrepancy. A discrepancy appears when $B_{1\,\mathrm{mult\,neut} \neq 2\pi^\circ}$ is limited by the use of: strong isospin conservation, the conserved vector current concept, and other data such as the measured cross sections for $e^+e^- \to$ hadrons. In Ref. 5, I used the work of Gilman and Rhie[1] to obtain

$$B_{1\,\mathrm{mult\,neut}}(\mathrm{calculated}) \leq 9.8\% \; . \tag{11}$$

Hence

$$B_{1\,\mathrm{mult\,neut} \neq 2\pi^\circ}(\mathrm{calculated}) \lesssim 3.2\% \; . \tag{12}$$

When Eq. (12) is used in Table 7, the discrepancy appears. There have been several[3,5,7,11] general discussions of this apparent discrepancy; I shall not repeat them here. I want to emphasize that the derivation of the discrepancy requires a combination of measurements and conventional theory. I now return to measurement issues, taking up first the problem of $B_{1\,\mathrm{mult\,neut}}$(measured).

IV. The Multiple Neutral Meson Modes

I will use data acquired with the Mark II detector at PEP to illustrate the obstacles to sorting out the modes:

$$\tau^- \to \nu_\tau + \pi^- + 2\pi^\circ \tag{1e}$$

$$\tau^- \to \nu_\tau + x^- + n\pi^\circ, \quad , \quad n \geq 3 \, , \tag{8a}$$

$$\tau^- \to \nu_\tau + x^- + \eta + n\pi^\circ, \quad , \quad n \geq 1 \, , \tag{8b}$$

$$\tau^- \to \nu_\tau + x^- + 2\eta + n\pi^\circ, \quad , \quad n \geq 0 \, . \tag{8c}$$

In this example, I have built on the research of my colleagues P. R. Burchat[12] and K. K. Gan.[13] I use the τ pair data sample of Ref. (12) in which a τ pair is selected by requiring that one of the decays have a single π or have three charged particles.

Table 8 divides the 1-charged particle modes of the other pair member according to the number of photons in that thrust axis hemisphere. The photons were required to have an energy greater than $E_{\gamma min}$, and to be separated from the charged track by at least 20 cm in the liquid argon calorimeter.

The division depends on the lower limit for the photon energy, $E_{\gamma min}$. The numbers of events with many photons decrease as $E_{\gamma min}$ increases for two reasons. First, decays with many photons have some lower energy photons. Second, some photons come from an interaction of the charged particle with detector material, not from the decay of the τ; and these usually have lower energy. The total number is slightly dependent on $E_{\gamma min}$ because of the selection method.

Suppose one wants to explain the relative numbers in Table 8 with the simplifying assumption that decays with at least one photon came from:

$$\tau^- \rightarrow \nu_\tau + \pi^- \ , \tag{13a}$$

$$\tau^- \rightarrow \nu_\tau + \rho^- \rightarrow \nu_\tau + \pi^- + \pi^\circ \ , \tag{13b}$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + 2\pi^\circ \ , \tag{13c}$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + 3\pi^\circ \ , \tag{13d}$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + 4\pi^\circ \ , \tag{13e}$$

One is ignoring: modes with η's; modes with unknown neutral particles that could be the cause of the discrepancy; and modes where the e or μ is associated with a photon due to internal or external radiation. Table 9 gives the relative efficiencies for the five modes in Eq. (13) as they would appear in the Mark II detector. In the simulation of the detector the following must be considered.

a. Some photons fall outside the fiducial volume of the photon detector. (In the Mark II, I use only the liquid argon calorimeter, 70% of 4π.)

b. Some photons have an energy below $E_{\gamma min}$

c. The two photons from a high energy π° may be detected as one photon. (Note: the $\tau^- \rightarrow \nu_\tau \rho^-$ mode for the Mark II.)

d. Photons may be produced by the π^- interacting in the detector's material. (In the Mark II, the π^- passes through the magnet coil before entering the liquid argon calorimeter, enhancing this problem.)

Applying the simulation calculation of Table 9 to the data of Table 8, there is much overlap of events from the decays in Eq. (134) with two or more π°'s. One can determine $B_{\pi 2\pi^\circ}$, although its value is sensitive[3,13] to assumptions about the existence of higher multiplicity neutral meson modes. The determination of $B_{\pi 3\pi^\circ}$ and $B_{\pi 4\pi^\circ}$ is unreliable even in this simplified example. The problem of separating all the modes in Eq. (8) by photon counting becomes impossible when one considers the realities: data is limited by statistics; there are uncertainties in the detector simulation; there are uncertainties in the decay dynamics of the various modes; there are backgrounds from other reactions; and the same number of photons can be produced by different modes, for example, $\nu_\tau \pi^- 4\pi^\circ$ and $\nu_\tau \pi^- \pi^\circ \eta$ with $\eta \to 3\pi^\circ$.

The example and these remarks are based on analyzing 29 GeV data using the Mark II detector. The analysis of existing data from other detectors exhibits similar problems, perhaps in different proportions. For example, in data[8] taken at about 10 GeV by the Crystal Ball detector, photon detection is much, much better, but the absence of a magnetic field allows much larger backgrounds. In summary, photon counting cannot be used in existing data to sort out all the various modes in Eq. (8).

Going beyond photon counting, special methods have been used to set limits on some modes. Lowe[8] analyzed Crystal Ball data by restricting the photons to special kinematic regions. Abachi et al[10] used the decay $\eta \to \pi^+\pi^-\pi^\circ$ and the principle of isospin conservation to set limits on modes containing η's. But at present there is no general method for finding the individual modes in Eq. (8).

We would be satisfied with a good measurement of $B_{1\,\mathrm{mult\,neut}}$, the sum of the branching fractions of all the modes in Eqs. (1e) and (8). The example shows why this is not available. Let $f_{\pi 3\pi^{\circ}}$ (3, 4) and $f_{\pi 3\pi^{\circ}}$ (> 4) be the relative efficiencies in Table 9 for the $\nu_{\tau}\pi^{-}3\pi^{\circ}$ mode to yield (3 or 4) or (> 4) photons; with similar notation for $\nu_{\tau}\pi^{-}4\pi^{\circ}$. Suppose that B_{π}, B_{ρ} and $B_{\pi 2\pi^{\circ}}$ are experimentally known so that one can calculate the residual number of events in Table 8 attributed to $\nu_{\tau}\pi^{-}3\pi^{\circ}$ and $\nu_{\tau}\pi^{-}4\pi^{\circ}$ called $N_{res}(1,2)$, $N_{res}(3,4)$ and $N_{res}(>4)$. Finally set $E_{\gamma min} = 0.4$ GeV in this example.

Statistical errors and errors in B_{π}, B_{ρ} and $B_{\pi 2\pi^{\circ}}$ preclude the use of $N_{res}(1,2)$ because the $\nu_{\tau}\pi^{-}3\pi^{\circ}$ and $\nu_{\tau}\pi^{-}4\pi^{\circ}$ contributions are relatively small. $N_{res}(3,4)$ is useful because $f_{\pi 3\pi^{\circ}}$ (3, 4) $\approx$ $f_{\pi 4\pi^{\circ}}$ (3, 4) in Table 9. Hence the use of only $N_{res}(3,4)$ could lead to the same value of $B_{1\,\mathrm{mult\,neut} \neq 2\pi^{\circ}}$ irrespective of the relative sizes of $B_{\pi 3\pi^{\circ}}$ and $B_{\pi 4\pi^{\circ}}$. On the other hand the use of only $N_{res}(>4)$ would lead to different values for $B_{1\,\mathrm{mult\,neut} \neq 2\pi^{\circ}}$, depending on the relative sizes of $B_{\pi 3\pi^{\circ}}$ and $B_{\pi 4\pi^{\circ}}$. The change could be as large as $f_{\pi 4\pi^{\circ}}$ (> 4)/$f_{\pi 3\pi^{\circ}}$ (> 4) = 1.7. In a real analysis, one effectively uses $N_{res}(1)$, $N_{res}(2)$, $N_{res}(3)$, ..., obtaining more discrimination. But there are uncertainties in the simulation calculations of the f's. And the number of different multiple neutral meson modes which are considered must still be severely limited. Hence the poor measurements of $B_{1\,\mathrm{mult\,neut}}$ in Table 5, and the weak limits

$$B_{1\,\mathrm{mult\,neut} \neq 2\pi^{\circ}}(\mathrm{measured}) \lesssim 10\% \ ,$$

$$B_{1\,\mathrm{mult\,neut}}(\mathrm{measured}) \lesssim 16\% \ .$$

Putting conventional theory and other data aside, one explanation for the discrepancy is that $B_{1\,\mathrm{mult\,neut}}$ is about 15%.

V. Other Experimental Issues

Other explanations of the discrepancy accept $B_{1\,\mathrm{mult\,neut}}(\mathrm{calculated}) \leq 9.8\%$, but look for mistakes in the measured values of $B_{e\mu\pi\rho K}$ or B_{1}. Three possibilities, not mutually exclusive, are (*a*) The measurement errors given by the experimenters are too small in one or more of the fractions: B_1, B_e, B_μ, B_π, and B_ρ.

(*b*) Most of the measurements of one or more of the fractions B_{1i} have the same unrecognized bias or asymmetric systematic error. Then the average measured $B_{e\mu\pi\rho K}$ could be smaller than the true $B_{e\mu\pi\rho K}$.

(*c*) Most of the measurements of B_1 have the same unrecognized bias or asymmetric systematic error such that the average measured B_1 is larger than the true B_1.

Hayes and I[4] have investigated possibility (a) by considering the five sets of measurements of B_1, B_e, B_μ, B_π, and B_ρ. For each set we compared the errors given for every measurement in the set with the scatter of every measurement about the formal average. Using this method, there is no evidence that experimenters are understating their errors; on the whole, the errors given by experimenters are reasonable.

The search for a widespread bias or asymmetric systematic error requires examination of a set of measurements and associated techniques. One must find an error being made by most of experimenters whose measurements are used to obtain B_1 or a particular B_{1i}. For example, T. Barklow, Y. S. Tsai and I have just begun to consider whether radiative effects in the decay of the τ are being treated correctly. There is no external evidence in the sets of measurements themselves for such an error. But if we were all making the same mistake, there might not be any external evidence.

I do not know if the discrepancy can be understood with existing τ decay data taken at SPEAR, CESR, DORIS, PEP or PETRA, or whether it can be understood using future data from existing detectors. If the problem lies in $B_{1\,\mathrm{mult\,neut}}$, this might not be possible. Improved detectors or new detectors specially built to study τ decays may be necessary.

References

1. GILMAN, F. J. & J. M. RHIE. 1985. Phys. Rev. **D31**:1066.
   GILMAN, J. F. 1987. Phys. Rev. **D35**:3541.
2. TRUONG, T. N. 1984. Phys. Rev. **D30**:1509.
3. GAM. K. K. & M. L. PERL. 1987. To be published in Int. J. Mod. Phys. **A**; also issued as SLAC–PUB–4331.
4. HAYES, K. G. & M. L. PERL. To be published.
5. PERL, M. L. 1987. To be published in Nucl. Phys. **B**, Proceedings Supplement; also issued as SLAC–PUB–4385.
6. AGUILAR–BENITEZ, M, ET AL. 1986. Phys. Lett. **170B**:6.
7. BARISH, B. C. & R. STROYNOUSKI. 1987. CALT–68–1425, submitted to Phys. Reports.
8. LOWE, S. T. 1987. SLAC–PUB–4449 and these Proceedings.
9. SPAAN, M. These Proceedings.
10. ABACHI, S., ET AL. 1987. Phys. Lett. **197B**:307.
11. GAN, K. K. 1987. To be published in Proceedings of 1987 SLAC Summer Institute; also issued as SLAC–PUB–4468.
12. BURCHAT, P. R., ET AL. 1986. Phys. Rev. **D35**:27.
13. GAN, K. K., ET AL. 1987. Phys. Rev. Lett. **59**:441.

Table 1. τ topological branching ratios in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 2.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

B_1		B_3		Experimental Group	Reference
Measurement	Combined Error	Measurement	Combined Error		
84.0	±2.0	15.0	±2.0	CELLO	Behrend, H.J. et al. 1982. Phys. Lett. **114B**:282.
$86.0 \pm 2.0 \pm 1.0$	±2.2	$14.0 \pm 2.0 \pm 1.0$	±2.2	MARK II	Blocker, C. A, et al. 1982. Phys. Rev. Lett. **49**:1369.
$85.2 \pm 1.9 \pm 1.3$	±2.3	$14.7 \pm 1.5 \pm 1.3$	±2.0	CELLO	Behrend, H. J, et al. 1984. Z. Phys. **C23**:103.
$84.7 \pm 1.1^{+1.6}_{-1.3}$	$^{+1.9}_{-1.7}$	$15.3 \pm 1.1^{+1.3}_{-1.6}$	$^{+1.7}_{-1.9}$	TASSO	Althoff, M., et al. 1985. Z. Phys. **C26**:521.
$86.7 \pm 0.3 \pm 0.6$	±0.7	$13.3 \pm 0.3 \pm 0.6$	±0.7	MAC	Fernandez, E., et al. 1985. Phys. Rev. Lett. **54**:1624.
$86.9 \pm 0.2 \pm 0.3$	±0.4	$13.0 \pm 0.2 \pm 0.3$	±0.4	HRS	Akerlof, C., et al. 1985. Phys. Rev. Lett. **55**:570.
$86.1 \pm 0.5 \pm 0.9$	±1.0	$13.6 \pm 0.5 \pm 0.8$	±0.9	JADE	Bartel, W., et al. 1985. Phys. Lett. **161B**:188.
$87.9 \pm 0.5 \pm 1.2$	±1.3	$12.1 \pm 0.5 \pm 1.2$	±1.3	DELCO	Ruckstuhl, W., et al. 1986.. Phys. Rev. Lett. **56**:2132.
$87.2 \pm 0.5 \pm 0.8$	±0.9	$12.8 \pm 0.5 \pm 0.8$	±0.9	MARK II	Schmidke, W. B., et al. 1986. Phys. Rev. Lett. **57**:527.
$84.7 \pm 0.8 \pm 0.6$	±1.0	$15.1 \pm 0.8 \pm 0.6$	±1.0	TPC	Aihara, H., et al. 1987. Phys. Rev. **D35**:1553.
86.6	±0.3	13.3	±0.3		Formal Average

Table 2. τ leptonic branching ratios in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Use $e-\mu$ Universality	$B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$		$B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$		Experimental Group	Reference
	Measurement	Combined Error	Measurement	Combined Error		
No			15.0	±3.0	PLUTO	Burmester, J., et al. 1977. Phys. Lett. **68B**:297.
No	16.0	±1.3			DELCO	Bacino, W.,et al. 1978. Phys. Rev. Lett. **41**:13.
No			17.8±2.0±1.8	±2.7	PLUTO	Berger, Ch., et al. 1981. Phys. Lett. **99B**:489.
Yes*	17.6±0.6±1.0	±1.3	17.1±0.6±1.0	±1.3	MARK II	Blocker, C. A., et al. 1982. Phys. Lett. **109B**:119
No	18.3±2.4±1.9	±3.1	17.6±2.6±2.1	±3.3	CELLO	Behrend, H. J., et al. 1983. Phys. Lett. **127B**:270
o	$20.4\pm3.0^{+1.4}_{-0.9}$	$^{+3.3}_{-3.1}$	$12.9\pm1.7^{+0.7}_{-0.5}$	±1.8	TASSO	Althoff, M., et al. 1985. Z. Phys. **C26**:521.
No	13.0±1.9±2.9	±3.5	19.4±1.6±1.7	±2.3	PLUTO	Berger, Ch., et al. 1985. Z. Phys. **C28**:1.
No	18.2±0.7±0.5	±0.9	18.0±1.0±0.6	±1.2	MARK III	Baltrusaitis, R. M., et al. 1985. Phys. Rev. Lett. **55**:1842.
No	17.4±0.8±0.5	±0.9	17.7±0.8±0.5	±0.9	MAC	Ash, W. W., et al. 1985. Phys. Rev. Lett. **55**:2118.
Yes*	17.8	±0.5	17.3	±0.5	MAC	Same data as above
No			17.4±0.6±0.8	±1.0	MARK J	Adeva, B., et al. 1986. Phys. Lett. **179B**:177.
No	17.0±0.7±0.9	±1.1	18.8±0.8±0.7	±1.1	JADE	Bartel, W., et al. 1986. Phys. Lett. **182B**:216.
No	18.4±1.2±1.0	±1.6	17.7±1.2±0.7	±1.4	TPC	Aihara, H., et al. 1987. Phys. Rev. **D35**:1553.
No	19.1±0.8±1.1	±1.4	18.3±0.9±0.8	±1.2	MARK II	Burchat, P. R., et al. 1987. Phys. Rev. **D35**:27.
	17.7	±0.4	17.7	±0.4		Formal Average

*Not included in formal average.

Table 3. $\tau^- \rightarrow \pi^- \nu_\tau$ branching ratio in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
9.0±2.9±2.5	±3.8	PLUTO	Alexander, G., et al. 1978. Phys Lett. **78B**:162.
11.7±0.4±1.8	±1.8	MARK II	Blocker, C. A., et al. 1982. Phys. Lett. **109B**:119.
9.9±1.7±1.3	±2.1	CELLO	Behrend, H. J., et al. 1983. Phys. Lett. **127B**:270.
11.8±0.6±1.1	±1.3	JADE	Bartel, W., et al. 1986. Phys. Lett. **182B**:216.
10.7±0.5±0.8	±0.9	MAC	Ford, W. T., et al. 1987. Phys. Rev. **D35**:408.
10.0±1.1±1.4	±1.8	MARK II	Burchat, P. R., et al. 1987. Phys. Rev. **D35**:27.
10.9	±0.6		Formal Average

Table 4. $\tau^- \to \rho^- \nu_\tau$ branching ratio in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
$22.1 \pm 1.9 \pm 1.6$	±2.5	CELLO	Behrend, H. J., et al. 1984. Z. Phys. **C23**:103.
$22.3 \pm 0.6 \pm 1.4$	±1.5	MARK II	Yelton, J. M., et al. 1986. Phys. Rev. Lett. **56**:812.
$23.0 \pm 1.3 \pm 1.7$	±2.1	MARK III	Adler, J., et al. 1987. Phys. Rev. Lett. **59**:1527.
$25.8 \pm 1.7 \pm 2.5$*	±3.0	MARK II	Burchat, P. R., et al. 1987. Phys. Rev. **D35**:27.
22.8	±1.0		Formal Average

*All $\tau^- \to \pi^- \pi^0 \nu_\tau$ included in $\tau^- \to \rho^- \nu_\tau$.

Table 5. Branching fractions $B_{\pi 2\pi^\circ}$ $B_{\pi 3\pi^\circ}$, and $B_{1\,\mathrm{mult\,neut}}$ in percent according to different assumptions as to modes included. The mode description uses a π^-, but the measured events may include those with a K^- instead of a π^-. The first error is statistical, the second systematic.

Modes Assumed	$B_{\pi 2\pi^\circ}$ (%)	$B_{\pi 3\pi^\circ}$ (%)	$B_{1\,\mathrm{mult\,neut}}$ (%)	Experimental Group	Reference
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$	$6.0 \pm 3.0 \pm 1.8$	$3.0 \pm 2.2 \pm 1.5$	9.0	CELLO	Behrend, H. J., et al. 1984. Z. Phys. **23**:103.
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$ $\pi^-\pi^0\eta\nu_\tau$			$13.9 \pm 2.0^{+1.9}_{-2.1}$	TPC	Aihara, H., et al. 1986. Phys. Rev. Lett. **57**:1836.
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$			$12.0 \pm 1.4 \pm 2.5$	MARK II	Burchat, R. R., et al. 1987. Phys. Rev. **D35**:27
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$	6.7 ± 0.5 *	2.2 ± 0.4	8.9	MARK II	Gan, K. K., et al. 1987. Phys. Rev. Lett. **59**:411.
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$ $\pi^-\pi^0\eta\nu_\tau$	$6.2 \pm 0.6 \pm 1.2$	$0.0^{+1.4}_{-0.0}{}^{+1.1}_{-0:0}$	10.4	MARK II	Same data as above
$\pi^-2\pi^0\nu_\tau$ $\pi^-3\pi^0\nu_\tau$	$8.7 \pm 0.4 \pm 1.1$			MAC	Band, H. R., et al. 1987. Submit. to Phys. Lett. SLAC–PUB–4333.
	7.5 ± 0.9	About 0. to 5.	About 9. to 16.		Average value

*Not used in computing average for $B_{\pi 2\pi^\circ}$

Table 6. Summary of measured branching fractions for modes with 1-charged particle in percent.

Type of Measurement	Row	Decay Mode	Branching Fraction (%)
Exclusive Measurements of Modes with 0 or 1 π°	A	$e^- \bar{\nu}_e \nu_\tau$	17.7 ± 0.4
	B	$\mu^- \bar{\nu}_\mu \nu_\tau$	17.7 ± 0.4
	C	$\mu^- \nu_\tau$	10.9 ± 0.6
	D	$\rho^- \nu_\tau$	22.8 ± 1.0
	E	$K^- \nu_\tau$, $K^{*-} \nu_\tau$	2.2 ± 0.3
Sum of rows A to E (Called $B_{e\mu\pi\rho K}$)	F		71.3 ± 1.3
$B_{\pi 2\pi^\circ}$	G	$\pi^- \pi^\circ \pi^\circ \nu_\tau$	7.5 ± 0.9
Sums of rows F + G $B_{e\mu\pi\rho K} + B_{i2\pi^\circ}$			78.8 ± 1.6

Table 7. Comparisons of $\sum_i B_{1i}$ with B_1 using either all measured B values or a combination of measured B values and calculations. All values in percent.

Row	Branching Fraction	All Measured B Values	Measured and Calculated B Values
A	$B_{e\mu\pi\rho K} + B_{\pi 2\pi^\circ}$	78.8 ± 1.6	78.8 ± 1.6 Measurement Only
B	$B_{1\,\text{mult neut} \neq 2\pi^\circ}$	~ 9	≤ 3.2 Calc. and Other Data
C	Rows $A + B$	$\lesssim 88.$	$\leq 82.0 \pm 1.6$
D	B_1	86.6 ± 0.3	86.6 ± 0.3 Measurement Only

Table 8. Observed number of 1-charged particle decays associated with various numbers of photons. $E_{\gamma \mathrm{min}}$ is the minimum energy of the photons counted.

$E_{\gamma min}$ (GeV)	Number of Associated Photons				
	all	0	1,2	3,4	> 4
0.2	2608	1507	808	238	55
0.3	2792	1683	854	225	30
0.4	2911	1798	899	203	11
0.5	2982	1885	922	169	6

Table 9. Relative efficiencies for detecting various numbers of photons as a function of the mode and $E_{\gamma\mathrm{min}}$, calculated by simulating the Mark II detector.

Mode	$E_{\gamma\mathrm{min}}$ (GeV)	Number of Associated Photons			
		0	1,2	3,4	> 4
$\nu_\tau \pi^-$	0.2	0.751	0.232	0.017	0.000
	0.3	0.787	0.203	0.010	0.000
	0.4	0.833	0.159	0.008	0.000
	0.5	0.860	0.136	0.004	0.000
$\nu_\tau \rho^-$	0.2	0.061	0.808	0.125	0.006
	0.3	0.088	0.822	0.090	0.000
	0.4	0.107	0.839	0.054	0.000
	0.5	0.141	0.816	0.043	0.000
$\nu_\pi^- 2\pi^\circ$	0.2	0.010	0.358	0.571	0.061
	0.3	0.015	0.450	0.505	0.030
	0.4	0.024	0.540	0.416	0.020
	0.5	0.028	0.607	0.356	0.009
$\nu_\pi^- 3\pi^\circ$	0.2	0.000	0.116	0.525	0.359
	0.3	0.006	0.165	0.574	0.255
	0.4	0.006	0.217	0.605	0.172
	0.5	0.014	0.278	0.622	0.086
$\nu_\pi^- 4\pi^\circ$	0.2	0.000	0.051	0.437	0.512
	0.3	0.002	0.079	0.503	0.416
	0.4	0.002	0.128	0.569	0.301
	0.5	0.002	0.186	0.630	0.182