SLAC – PUB – 4609
April 1988
(E)

REVIEW OF RECENT RESULTS ON THE τ LEPTON*

K. K. GAN
Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309, USA

ABSTRACT

This is a review of the recent results on the τ lepton. The results include precise measurements of the lifetime, measurements of the decay $\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$ with much improved precision, limits on decay modes containing η mesons, including the second-class-current decay $\tau^- \rightarrow \pi^- \eta \nu_\tau$, and limits on exotic decay modes. The implications of these results on the discrepancy in the one-charged-particle decay modes are discussed.

Invited talk presented at the XXIIIrd Rencontre de Moriond:
Electroweak Interactions and Unified Theories
Les Arcs, Savoie, France, March 6 – 12, 1988

---

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

1. INTRODUCTION

The τ lepton has been a subject of extensive study since the discovery[1] in 1975. All measurements[2] indicate that it is a sequential lepton in the standard gauge theory of electromagnetic and weak interactions. The branching ratios for most of the major decay modes have been measured with good precision and all measurements are in good agreement with the theoretical expectations. However, the sum of the measured branching ratios for decay modes with one charged particle in the final state is significantly smaller than the inclusive measurement.[3] Since the theoretical predictions for the branching ratios and the τ lifetime are related to the electron branching ratio, measurement of the lifetime provides an independent measurement of the electron branching ratio. There are several new and precise measurements of the lifetime. We review the results in the next section. We then review the new results on the decay $\tau^- \to \pi^- 2\pi^0 \nu_\tau$, which has now been measured with much improved precision. Also included is a discussion of the decay $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Then, we survey the theoretical expectations and experimental limits on decay modes containing η mesons including the limits on the second-class-current decay $\tau^- \to \pi^- \eta \nu_\tau$. New limits on the exotic decays which violate lepton number conservation will also be discussed. We conclude with a discussion of the implications of the new results on the discrepancy in the one-charged-particle decay modes.

2. LIFETIME

Measurement of the τ lifetime provides a direct study of the coupling strength of the τ to the charged weak current. In the standard model, the τ decay $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ proceeds in perfect analogy to the μ decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$. Assuming $\mu - \tau$ universality of the weak coupling and that the τ neutrino is massless, the τ lifetime is related to the μ lifetime by[4]

$$\begin{aligned} \tau_\tau &= \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu \, B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \\ &= 16.03 \times 10^{-13} \, B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \text{ s} \quad . \end{aligned}$$

With the world average measurement[2] of the electron branching ratio $B_e = (17.7 \pm 0.4)\%$, the predicted lifetime is $\tau_\tau = (2.83 \pm 0.06) \times 10^{-13}$ s.

Several experiments[5-11] have new measurements of the τ lifetime. All measurements are consistent with each other as shown in fig. 1. The weighted average of the measurements is $\tau_\tau = (3.03 \pm 0.08) \times 10^{-13}$ s, in fair agreement with the theoretical prediction. The implication of the result on the discrepancy in the one-charged-particle decay modes will be discussed in sec. 4.

3. DECAY MODES AND BRANCHING RATIOS

The τ decay is a good laboratory for studying many aspects of the standard model. Since the τ appears to have no internal structure to complicate theoretical calculations, many branching ratios can be predicted with the present understanding of the electroweak interaction. The large lepton mass allows the τ to decay into both purely leptonic states and semi-leptonic states with accompanying hadrons. In this section, we review the new results on branching ratios.

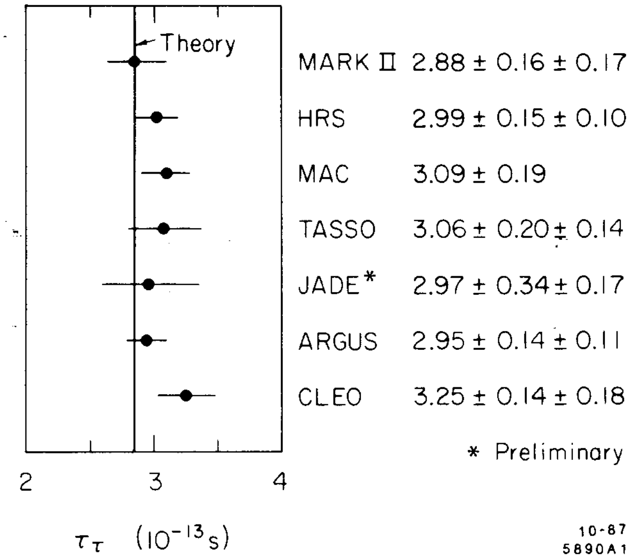

Fig. 1. τ lifetime measurements.

3.1 3π and 4π Decays

The three-pion decay of the τ is mediated by the axial-vector part of the weak interaction. The branching ratio can be estimated using the partially-conserved-axial-current[12] (PCAC) hypothesis. Unfortunately, the estimate is not very reliable. However, isospin conservation imposes a limit on the relative fraction of the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$: $B_{\pi 2\pi^0} \leq B_{3\pi}$. If the decay is dominated by the $a_1(1270)$ resonance as expected, then $B_{\pi 2\pi^0} = B_{3\pi}$. The world average measurement[2] of $B_{3\pi}$ is $(6.7 \pm 0.4)\%$.

The four-pion decay proceeds through the vector current and can be estimated[4] by the conserved-vector-current (CVC) hypothesis.[13] Gilman and Rhie[3] use the measured cross sections for $e^+e^- \to \pi^+\pi^-2\pi^0$ and $e^+e^- \to 2\pi^+2\pi^-$ to calculate the branching ratios for $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-3\pi^0\nu_\tau$, and predict $B_{3\pi\pi^0} = 0.275 \times B_e = 4.9\%$ and $B_{\pi 3\pi^0} = 0.055 \times B_e = 1.0\%$. The world average measurement[2] of $B_{3\pi\pi^0}$ is $(5.0 \pm 0.5)\%$, in good agreement with the CVC prediction.

It is difficult to measure $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ because of the multiple photons in the final states, which demand good energy resolution and granularity for the electromagnetic shower detection. Four years ago, the CELLO collaboration reported measurements[14] of the branching ratios by unfolding the observed photon multiplicity spectrum. The results are

$$\begin{aligned} B_{\pi 2\pi^0} &= (6.0 \pm 3.0 \pm 1.8)\% \\ B_{\pi 3\pi^0} &= (3.0 \pm 2.2 \pm 1.5)\% \quad . \end{aligned} \tag{1}$$

The measurements ignored the contributions from decays containing η mesons such as $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ and $\tau^- \to \pi^-\eta\eta\nu_\tau$.

There are now three new measurements of the branching ratios. The MARK II collaboration[15] extracted the branching ratios by fitting the observed photon multiplicity spectrum of τ candidates with one charged particle and three or more photons. The fit favored additional multiple-neutral-meson decay modes other than $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Using the decay $\tau^- \to \pi^- \eta\pi^0 \nu_\tau$ as an example for the multiple-neutral-meson decay modes, the fit yields

$$B_{\pi 2\pi^0} = (6.2 \pm 0.6 \pm 1.2)\% \quad ,$$
$$B_{\pi 3\pi^0} = \left(0.0 \pm^{1.4}_{0.0} \pm^{1.1}_{0.0}\right)\% \quad , \qquad (2)$$
$$B_{\pi\eta\pi^0} = \left(4.2 \pm^{0.7}_{1.2} \pm 1.6\right)\% \quad .$$

The MAC collaboration[16] measured $B_{\pi 2\pi^0}$ by using τ candidates with two energetic photons. The invariant mass of the two photons was required to be greater than 200 MeV/c^2 to reduce contamination from the decay $\tau^- \to \pi^- \pi^0 \nu_\tau$. The result is

$$B_{\pi 2\pi^0} = (8.7 \pm 0.4 \pm 1.1)\% \quad . \qquad (3)$$

The CRYSTAL BALL collaboration measured[17] $B_{2\pi^0}$ using τ candidates with four detected photons. Figure 2(a) shows the invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against another $\gamma\gamma$ pair which has an invariant mass that is consistent with the π^0 mass. A clear π^0 signal is evident. This is the first direct evidence of this decay mode; the excellent resolution of the CRYSTAL BALL allows the reconstruction of the π^0's amid the large combinatorial background. The result of a fit to the mass spectrum yields

$$B_{\pi 2\pi^0} = (7.4 \pm 0.6 \pm 1.3)\% \quad . \qquad (4)$$

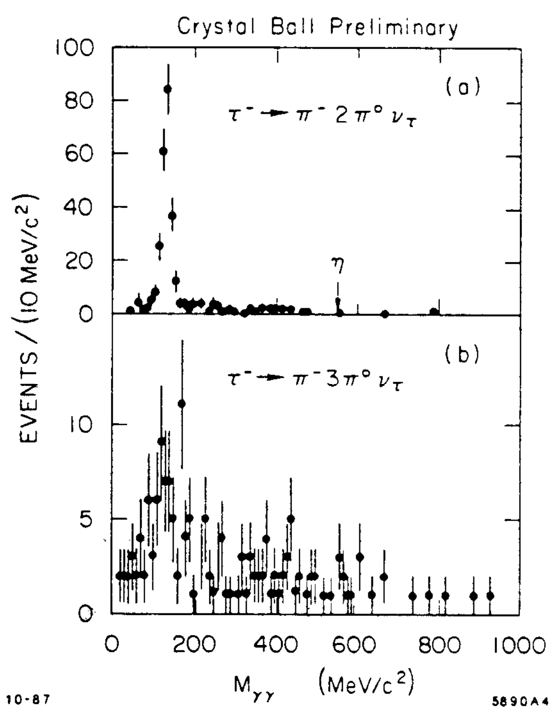

Fig. 2. Invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against (a) another $\gamma\gamma$ pair which has an invariant mass that is consistent with the π^0 mass, (b) two other $\gamma\gamma$ pairs which both have an invariant mass that is consistent with the π^0 mass.

The CRYSTAL BALL also performed a similar analysis on the six-photon sample to measure $B_{\pi 3\pi^0}$. Figure 2(b) shows the invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against two other $\gamma\gamma$ pairs which both have an invariant mass that is consistent with the π^0 mass. There is no clear evidence for a π^0 signal due to the very large combinatorial background and the limited detection efficiency. A fit to the mass spectrum yields

$$B_{\pi 3\pi^0} = (0.54 \pm 0.28 \pm 1.06)\% \tag{5}$$

or an upper limit of

$$B_{\pi 3\pi^0} < 2.5\% \tag{6}$$

at the 95% confidence level.

Within the errors, all measurements of $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are consistent with the theoretical expectations. The result from MARK II on $B_{\pi\eta\pi^0}$ will be discussed in sec. 3.3.

Since the τ decays into the 4π final state with a substantial rate of several percents and the decay is expected to proceed through the $\rho(1600)$, one would expect a significant rate into the 2π final state with high mass, an effect not observed in the data.[18] I have calculated[19] the 2π mass spectrum from the measured cross section of $e^+e^- \to \pi^+\pi^-$ using CVC and compare the prediction with the MARK II data. This comparison of the shape of the spectra allows a precise test of CVC. The data is consistent with the prediction as shown in fig. 3, including the high mass region.

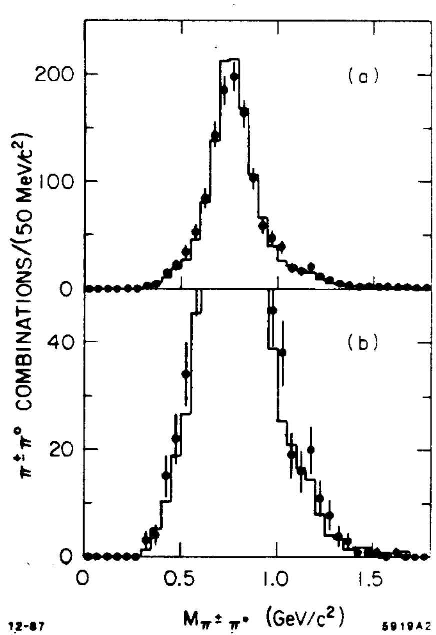

Fig. 3. The $\pi^+\pi^-$ invariant mass spectrum, as measured by the MARK II collaboration together with the CVC prediction (histogram), normalized to the same number of events. Figure 3(b) is an enlarged view of fig. 3(a).

This reaffirms the validity of CVC and indicates that $\rho(1600)$ may decay into 2π at a rate significantly smaller than that of the Particle Data Group compilation.[20] Similar analysis can also be performed on the 4π decay.

3.2 $\pi\eta$ Decay

In the last Moriond conference, the HRS collaboration reported evidence[21] for the second-class-current decay $\tau^- \to \pi^-\eta\nu_\tau$ with a branching ratio of

$$B_{\pi\eta} = (5.1 \pm 1.0 \pm 1.2)\% \quad . \tag{7}$$

It is rather difficult,[22,23] even in nonstandard models, to account for such a large branching ratio of a few percent as reported. Since then, many experiments[17,24–29] have searched for the decay and fail to confirm the HRS finding. Limits obtained from the experiments are summarized in table 1.

Table 1. Upper limits on the branching ratio in percent for $\tau^- \to \pi^-\eta\nu_\tau$.

Limit	Confidence Level (%)	Technique	Experimental Group	Reference
2.5	90	$\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$	MARK III	24
2.3	95	$\eta \to \pi^+\pi^-(\pi^0)$	HRS	25
1.8	95	$\eta \to \pi^+\pi^-\pi^0$	CLEO	26
1.7	95	$\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$	CELLO	27
1.3	95	$\eta \to \pi^+\pi^-\pi^0$	ARGUS	28
1.0	95	$\eta \to \gamma\gamma$	MARK II	29
0.3	95	$\eta \to \gamma\gamma$	CRYSTAL BALL*	17
1.3	95	$\tau^- \to K^-K^0\nu_\tau$	TPC	31

*Preliminary

The HRS collaboration also searched[25] for the η signal using the decay $\eta \to \pi^+\pi^-\pi^0$ in a subsequent analysis. The experiment searched for an enhancement in the $\pi^+\pi^-$ invariant mass distribution of τ candidates with three charged particles and one or more photons. The low Q^2 of the η decay restricts the invariant mass to be in a relatively narrow range,

$$280 < m_{\pi^+\pi^-} < 410 \text{ MeV/c}^2$$

$$m_{2\pi} \qquad\qquad\qquad m_\eta - m_\pi \quad .$$

The invariant mass rises slowly from the lower kinematic limit at 280 MeV/c^2 to a peak near 380 MeV/c^2, and then drops steeply to the upper kinematic bound at 410 MeV/c^2. The analysis took advantage of the excellent momentum resolution of the HRS without using the electromagnetic calorimeter information. No enhancement at 380 MeV/c^2 was observed, resulting in an upper limit of 2.3% at the 95% confidence level.

The second-class-current decay should also give rise[22,30] to an SU(3) related decay, $\tau^- \rightarrow K^- K^0 \nu_\tau$. The TPC collaboration has searched[31] for the decay but to no avail, resulting in an upper limit of $B_{KK^0} < 0.26\%$ at the 95% confidence level. With the assumption of an approximate flavor SU(3) symmetry,[30] the TPC limit corresponds to $B_{\pi\eta} < 5.1 \times B_{KK^0} < 1.3\%$.

In conclusion, there is no evidence for second class currents. It appears that the η signal observed by HRS is a statistical fluctuation.[25]

3.3 $2\pi\eta$ Decay

The decay $\tau^- \rightarrow \pi^- \eta \pi^0 \nu_\tau$ is allowed in the standard model and is expected to proceed through the $\rho(1600)$ resonance. Using the measured cross section for $e^+e^- \rightarrow \eta\pi^+\pi^-$ together with the CVC hypothesis, Gilman predicts[32] the branching ratio to be $B_{\pi\eta\pi^0} = 0.15\%$. It is difficult to measure the branching ratio because of the multiple photons in the final state. As discussed in Sec. 3.1, the MARK II collaboration,[15] using the decay as an example of the multiple-neutral-meson decay modes, obtained $B_{\pi\eta\pi^0} = (4.2 \pm^{0.7}_{1.2} \pm 1.6)\%$ from the fit. This is significantly larger than the theoretical prediction. This, however, is not a meaningful comparison as the decay is used as an example of the multiple-neutral-meson decays and the detector is insensitive to the η signal due to the limited mass resolution and the large combinatorial problem. Note that the results on $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are relatively insensitive to the assumption.

The HRS search[25] for the η signal using the $\pi^+\pi^-$ invariant mass technique is also valid for $\tau^- \rightarrow \pi^- \eta \pi^0 \nu_\tau$ because the search is relatively insensitive to the number of π^0's accompanying the η. Therefore the upper limit for the branching ratio is $B_{\pi\eta\pi^0} < 2.3\%$ at the 95% confidence level. The CLEO collaboration used[26] the same technique and set an upper limit of 2.1%.

The CRYSTAL BALL collaboration searched for the decay in both an exclusive[17] and an inclusive analysis.[33] The exclusive analysis searched for an η signal in the four-photon sample. No enhancement was observed as shown in fig. 2(a), resulting in an upper limit of $B_{\pi\eta\pi^0} < 2.5\%$ at the 95% confidence level. The inclusive analysis searched for an η signal in τ candidates with two or more photons. The inclusive sample has somewhat more background, but much larger detection efficiency, and hence a more stringent limit, $B_{\pi\eta\pi^0} < 0.9\%$.

3.4 $3\pi\eta$ Decay

There are no firm theoretical predictions on the branching ratios for the decays $\tau^- \rightarrow \pi^- \eta \pi^+ \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \eta 2\pi^0 \nu_\tau$. However, the two branching ratios are related by isospin invariance: $B_{\pi\eta 2\pi^0} \leq B_{3\pi\eta}$.

The HRS collaboration also used the $\pi^+\pi^-$ invariant mass technique[25] to set an upper limit on $B_{3\pi\eta}$. The experiment searched for $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2 in the six τ candidates with five charged particles and one or more photons. All the candidates were found to contain at least one valid combination. Attributing all the candidates to the η decay yields the limit $B_{3\pi\eta} < 0.4\%$ at the 95% confidence level. From isospin invariance, therefore, $B_{\pi\eta 2\pi^0} < 0.4\%$.

As in the previous section, the limit on $B_{3\pi\eta}$ also applies for the case where the η is accompanied by π^0's. Note that the *experimental* limit on $B_{\pi\eta 2\pi^0}$ is 2.3% from the HRS collaboration[25] and 2.1% from the CLEO collaboration.[26]

3.5 $\pi 2\eta$ Decay

There is also no firm theoretical prediction on the branching ratio for $\tau^- \to \pi^- 2\eta\nu_\tau$. However, there is an experimental limit[25] on the decay from the HRS collaboration using the $\pi^+\pi^-$ invariant mass technique.

The experiment searched in the 5-prong sample for events that contained at least two separate $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2 and found one event. This results in the upper limit of $B_{\pi 2\eta} < 0.6\%$ at the 95% confidence level. As before, this limit also applies if the η's are accompanied by π^0's.

The CRYSTAL BALL collaboration[17] also searched for $\tau^- \to \pi^- 2\eta\nu_\tau$, with both η's decaying into $\gamma\gamma$, in the four-photon sample. No η enhancement was observed, resulting in upper limit of $B_{\pi 2\eta} < 1.4\%$ at the 95% confidence level. The null result[33] in the search for an inclusive η signal was also used to place a limit on the decay, $B_{\pi 2\eta} < 2.5\%$. This limit is less stringent because of the larger background.

3.6 Exotic Decay Modes

Lepton number conservation is an experimentally observed phenomenon, it is not required in the standard model. The search for a lepton number violating decay probes for an effect in the energy scale well above the reach of present colliders. The observation of a lepton number violating decay might indicate the existence of a new particle or interaction. The CRYSTAL BALL Collaboration has reported preliminary limits[34] on decays involving an electron and a photon or hadron,

$$B(\tau^- \to e^-\gamma) < 2.0 \times 10^{-4} ,$$

$$B(\tau^- \to e^-\pi^0) < 1.4 \times 10^{-4} ,$$

$$B(\tau^- \to e^-\eta) < 2.4 \times 10^{-4} ,$$

at the 90% confidence level. The limits on $e\gamma$ and $e\pi^0$ represent significant improvements over the previous MARK II limits[35] while no other limit on $e\eta$ exist.

In a related analysis, I have studied[36] the e to τ coupling: if there is a new hypothetical particle Z' that induces a lepton number violating process, such as $\mu^- \to e^-e^+e^-, \tau^- \to e^-\mu^+e^-$, $K_L^0 \to e^+\mu^-$, it could also affect the reactions $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to \tau^+\tau^-$ through its t-channel exchange. The new interaction is assumed to be a four-fermion point interaction with a V-A structure. A fit of the cross sections and asymmetries of the reactions measured by experiments at PEP and PETRA yields the following 90% confidence level limits on the coupling:

$$G_{e\mu} < 0.119 \quad G_F \quad ,$$

$$G_{e\tau} < 0.085 \quad G_F \quad ,$$

where G_F is the Fermi Coupling constant. Therefore a limit on e to τ coupling more than ten times weaker than the weak scale has been obtained.

The limit on the branching ratio for the decay $\tau^- \to e^-\mu^+e^-$ yields the following limit on the product of couplings,

$$(G_{e\mu}G_{e\tau})^{1/2} < 1.4 \times 10^{-2}\ G_F \quad .$$

Therefore the limit on the product of couplings obtained from the fit is not as stringent. However, the individual limits on $G_{e\mu}$ and $G_{e\tau}$ exclude some of the regions allowed by the decay search as shown in fig. 4. Similar limits on the products of couplings can also be obtained from the limits on the exotic decays discussed above or from other exotic decays[2] such as $\tau^- \to e^-e^+e^-$, $\tau^- \to e^-\mu^+\mu^-$. Some of these limits involve diagonal couplings. Comparison with these limits will be meaningless if, for some unknown reasons, the diagonal couplings are very small or zero. In all cases, the limits obtained from the fit exclude some of the regions allowed by the decay search. Prospect for improvement in the near future is good.[36]

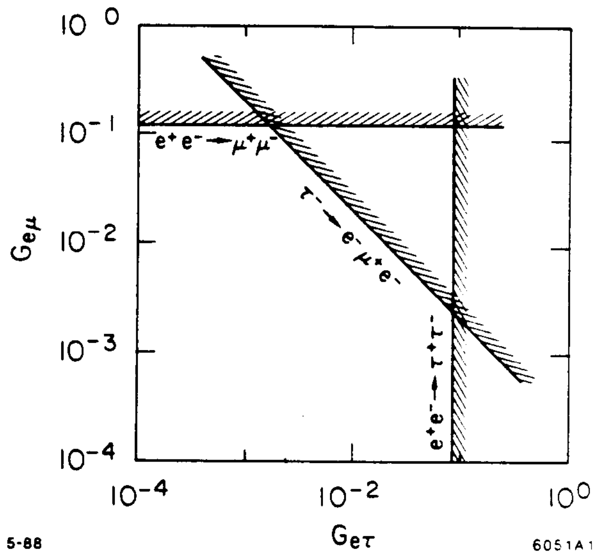

Fig. 4. 90% confidence level limits on $G_{e\mu}$ and $G_{e\tau}$, in unit of G_F.

4. COMPARISON OF INCLUSIVE AND EXCLUSIVE BRANCHING RATIOS

In this section, we discuss the implications of the new results on the discrepancy in the one-charged-particle decay modes. Table 2 summarizes the experimental measurements and theoretical expectations for the exclusive branching ratios. All measurements are in good agreement with the expectations. The world average inclusive measurements[2] of the one- and three-charged-particle branching ratios are $B_1 = (87.0 \pm 0.3)\%$ and $B_3 = (12.9 \pm 0.3)\%$, respectively.[37] The sum of the two exclusive three-charged-particle branching ratios is in fair agreement with the inclusive measurement. For the one-charged-particle final states, the sum of the exclusive branching ratios is significantly less than the inclusive measurement. Thus, there is still a discrepancy between the measured inclusive one-charged-particle branching ratio and the new sum of exclusive measurements.

The new measurements of τ lifetime indicate that the major decay branching ratios should be a few percent larger. The world average measurement of the lifetime (sec. 2) is somewhat larger than the prediction based on the world average measurement of the electron branching ratio. The lifetime measurement corresponds to $B_e = (18.9 \pm 0.5)\%$. If the actual values of the major decay branching ratios correspond to this value of B_e, then the actual sum of the exclusive branching ratios would be considerably larger and removes any serious discrepancy between the inclusive and the exclusive measurements. However, it is very difficult to understand why all the major exclusive branching ratios currently measured are significantly below their actual values. But then, there have been times in physics when a quantity was consistently measured slightly wrong because the "follow-the-crowd" effect led experimenters to seek and correct errors in just one direction. In view of the fact that measurement of the lifetime is far more complicated than measurements of the exclusive branching ratios, the lifetime measurements can only be regarded as an indication.

Table 2. Experimental measurements and theoretical expectations for the branching ratios.

Decay Mode	Branching Ratio (%)	
	Experimental	Theory
1-prong:		
e	17.7 ± 0.4	17.7
μ	17.7 ± 0.4	17.2
π	10.9 ± 0.6	10.7
K	0.6 ± 0.2	0.7
ρ	22.8 ± 0.9	21.8
K^*	1.6 ± 0.3	1.1
$\pi 2\pi^0$	7.5 ± 0.7	6.7
$\pi 3\pi^0$	"1.0"	1.0
$\pi\eta\pi^0$	<0.9	0.15
$\pi\eta 2\pi^0$	<2.1	<0.4
$\pi 2\eta$	<0.6	
$\pi 4\pi^0 + \pi 5\pi^0$		<0.10
TOTAL	79.8 ± 1.5	
3-prong:		
3π	6.7 ± 0.4	
$3\pi\pi^0$	5.0 ± 0.5	4.9
TOTAL	11.7 ± 0.6	
5-prong:		
$5\pi + 5\pi\pi^0$	0.11 ± 0.03	

It is unlikely that the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ are large enough to account for the discrepancy. The results on $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ from MARK II, MAC and CRYSTAL BALL (sec. 3.1) are consistent with each other and the expectation assuming isospin invariance. The branching ratio[8] for $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ is predicted to be 1%. The experimental "measurements" from MARK II and CRYSTAL BALL (sec. 3.1) indicate that the branching ratio is not large.

It is also unlikely that the branching ratios for decay modes containing η mesons are large enough to resolve the discrepancy. The largest decay mode is expected to be $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$. The branching ratio is predicted[32] to be $B_{\pi\eta\pi^0} = 0.15\%$ by Gilman using the measured cross section of $e^+e^- \to \eta\pi^+\pi^-$. It is unlikely that $B_{\pi\eta\pi^0}$ can be significantly larger than this value due to possible errors in the cross section measurements.[38] This is supported by experimental measurements (sec. 3.3) — the CRYSTAL BALL collaboration set an upper limit of $B_{\pi\eta\pi^0} < 0.9\%$ at the 95% confidence level.[33] The limits on other decay modes containing η mesons are also stringent as summarized in table 2. The experimental limits are inclusive as they are relatively insensitive to the number of π^0's accompanying the η's.

There is a possible experimental solution to the problem although it defies conventional theoretical explanations. Two experiments have measured the inclusive branching ratio with multiple neutral mesons in the final states. The TPC collaboration extracted[39] the branching ratio by measuring the number of τ candidates with one charged particle and three or more photons, with the invariant mass of at least one $\gamma\gamma$ combination consistent with the π^0 mass. The experiment assumed that the τ candidates were dominated by the decays $\tau^- \to \pi^- 2\pi^0 \nu_\tau$, $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ and $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$ and obtained a weighted sum measurement of

$$B_{\pi 2\pi^0} + 1.6 B_{\pi 3\pi^0} + 1.1 B_{\pi\eta\pi^0} = (13.9 \pm 2.0 \pm 1.9)\% \quad .$$

This is somewhat larger than the theoretical prediction of $\sim 8.5\%$. The MARK II collaboration[40] extracted an inclusive branching ratio by measuring the number of τ candidates with two or more energetic photons. Ignoring the decay modes containing η mesons, the experiment found

$$B_{\pi 2\pi^0} + B_{\pi 3\pi^0} = (12.0 \pm 1.4 \pm 2.5)\% \quad .$$

This is also somewhat larger than the theoretical expectation of $\sim 7.7\%$. As discussed in sec. 3.1, the experiment performed a further analysis[15] to extract the exclusive branching ratios by fitting the observed photon multiplicity spectrum. The fit favored additional multiple-neutral-meson decays other than $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Using the decay $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$ as an example for the multiple-neutral-meson decays, the fit yields

$$B_{2\pi^0} = (6.2 \pm 0.6 \pm 1.2)\% \quad ,$$

$$B_{3\pi^0} = (0.0 \pm^{1.4}_{0.0} \pm^{1.1}_{0.0})\% \quad ,$$

$$B_{\pi\eta\pi^0} = (4.2 \pm^{0.7}_{1.2} \pm 1.6)\% \quad .$$

The excessive branching ratio for $B_{\pi\eta\pi^0}$ implies that there are more events with multiple neutral mesons than expected.

There is another indication of an excess from the MAC collaboration.[16] As discussed in sec. 3.1, the experiment extracted the branching ratio for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$

by measuring the number of τ candidates with one charged particle and two energetic photons. The result is

$$B_{\pi 2\pi^0} = (8.7 \pm 0.4 \pm 1.1)\% \quad .$$

This is somewhat larger than the expectation from isospin invariance, $B_{\pi 2\pi^0} = B_{3\pi} = (6.7 \pm 0.4)\%$. As the experiment is very sensitive to feed down from other multiple-neutral-meson decays, the result indicates that there may be an excess of multiple-neutral-meson decays.

Therefore three experiments seem to observe an excess of multiple-neutral-meson decays, although defying conventional explanations, that could at least partially account for the discrepancy. It remains an experimental challenge to see whether we can convincingly establish the existence of an excess and, if it exists, determine which modes comprise it and whether there are any exotic decay modes.

One possible explanation for the discrepancy due to the existence of a massive τ-neutrino-like neutral lepton has been explored by Perl.[41] The τ decays involving the massive neutral lepton will be mostly one-charged-particle final states due to the energy carried away by the massive lepton. The average momenta of the charged particles will be lower than those involving the light τ neutrino and may not be accepted in the exclusive branching ratio measurements while being accepted in the inclusive measurements due to the lower minimum momentum requirements and thus provide a possible explanation for the discrepancy. Perl finds that this effect is not large enough to account for the discrepancy if the massive neutral lepton prescribes to the conventional weak interaction: consider the two extremes, if the mass of the neutral lepton is close to the τ mass, the decays involving the massive lepton will be so suppressed that the discrepancy due to the loss of events will be very small, on the other extreme, if the neutral lepton is light ($\lesssim 1$ GeV/c^2), the difference in the detection efficiencies for the two types of neutral leptons will be too small to produce a discrepancy. Regardless of the mass of the neutral lepton, the discrepancy is always less than 1% and thus too small to account for the discrepancy. Note that comparison of the measurements of the τ lifetime and the leptonic branching ratios excludes a neutral lepton of mass less than 1 GeV/c^2.

Hayes and Perl have performed a comprehensive statistical study[42] of some 60 different measurements of the branching ratios and lifetime to investigate whether the discrepancy is caused by an underestimate of the error or by a bias in some of the measurements. The study assumes a normal error distribution and that there is no correlation between the systematic errors of different experiments. By comparing the errors and the scatter of the measurements around the mean, the authors find that there is indication that the measurements[43] of B_e, B_π and B_ρ are overconsistent. From an analysis with the statistical errors only, they conclude that there is clear evidence of clustering in the B_ρ measurements, and hints of clustering in other measurements. The error on the average of the B_ρ measurements may be too small because of the bias and the discrepancy may therefore be reduced. However, there is no evidence that the bias causes the discrepancy in summing the branching ratios since it is not possible to evaluate the size and sign of the bias.

It should be emphasized that not a single experiment sees a significant discrepancy in the one-charged-particle decays, as it is just at the limit of the statistical and systematic errors of one experiment. Yet it is still an intriguing puzzle that may require major detective work.

CONCLUSION

With the new measurements of the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ and the stringent limits on the decay modes containing η mesons, we have exhausted the conventional decay modes to account for the discrepancy. This deepens the mystery in the apparent excess of multiple-neutral-meson decays. However, the measurement of lifetime indicates that the branching ratios of all the major decay modes should be larger. This, although difficult to understand experimentally, could be a potential solution to the discrepancy.

In conclusion, despite the tremendous progress in the last few years, the discrepancy is still unsolved and, if anything, has deepened.

ACKNOWLEDGEMENTS

I am greatly indebted to my colleague M. L. Perl for many useful discussions.

REFERENCES

1. M. L. Perl et al., Phys. Rev. Lett. **35,** 1489 (1975).
2. For a recent review see, for example, K. K. Gan, SLAC–PUB–4468, to be published in Proc. of the SLAC Summer Institute on Particle Physics, Stanford, California, 1987; K. K. Gan and M. L. Perl, Int. J. Mod. Phys. **A3,** 531 (1988).
3. F. J. Gilman and S. H. Rhie, Phys. Rev. **D31,** 1066 (1985).
4. Y. S. Tsai, Phys. Rev. **D4,** 2821 (1971); H. B. Thacker and J. J. Sakurai, Phys. Lett. **36B,** 103 (1971).
5. D. Amidei et al., Phys. Rev. **D37,** 1750 (1988).
6. S. Abachi et al., Phys. Rev. Lett. **59,** 2519 (1987).
7. H. R. Band et al., Phys. Rev. Lett. **59,** 415 (1987).
8. W. Braunschweig et al., DESY 88–034, 1988 (unpublished).
9. W. Bartel et al., contributed paper to Int. Sym. Lepton and Photon Interactions at High Energies, Hamburg, 1987.
10. H. Albrecht et al., Phys. Lett. **199B,** 580 (1987).
11. C. Bebek et al., Phys. Rev. **D36,** 690 (1987).
12. J. Bernstein et al., Nuovo Cimento **17,** 757 (1960).
13. R. P. Feynman and M. Gell–Mann, Phys. Rev. **109,** 193 (1958).
14. H. J. Behrend et al., Z. Phys. **C23,** 103 (1984).
15. K. K. Gan et al., Phys. Rev. Lett. **59,** 411 (1987).
16. H. R. Band et al., Phys. Lett. **198B,** 297 (1987).

17. S. T. Lowe, SLAC Preprint No. SLAC–PUB–4449, to be published in Proc. of the Int. Symp. Production and Decay of Heavy Flavors, Stanford, California, 1987. All results are preliminary.

18. See, for example, the 2π mass spectrum in J. M. Yelton et al., Phys. Rev. Lett. **56**, 812 (1986) and J. Adler et al., Phys. Rev. Lett. **59**, 1527 (1987).

19. K. K. Gan, SLAC–PUB–4512, 1988 (submitted to Phys. Rev. D).

20. Particle Data Group, M. Aguilar–Benitez et al., Phys. Lett. **170B**, 1 (1986).

21. J. Repond, Proc. XXII Rencontre de Moriond, Standard Model: Supernova 1987a (Les Arcs, Savoie, France, 1987), ed. J. Tran Thanh Van, p. 561; M. Derrick et al., Phys. Lett. **189B**, 260 (1987).

22. E. L. Berger and H. J. Lipkin, Phys. Lett. **189B**, 226 (1987).

23. C. K. Zachos and Y. Meurice, Mod. Phys. Lett. **A2**, 247 (1987).

24. D. Coffman et al., Phys. Rev. **D36**, 2185 (1987).

25. S. Abachi et al., Phys. Lett. **197B**, 291 (1987).

26. P. Baringer et al., Phys. Rev. Lett. **59**, 1993 (1987).

27. H. J. Behrend et al., Phys. Lett. **200B**, 226 (1988).

28. H. Albrecht et al., Phys. Lett. **195B**, 307 (1987).

29. K. K. Gan et al., Phys. Lett. **197B**, 561 (1987).

30. M. Suzuki et al., Phys. Rev. **D36**, 950 (1987).

31. H. Aihara et al., Phys. Rev. Lett. **59**, 751 (1987).

32. F. J. Gilman, Phys. Rev. **D35**, 3541 (1987).

33. T. Skwarnicki, to be published in Proc. Int. Europhysics Conf. High Energy Physics, Uppsala, 1987.

34. D. Antreasyan et al., HEN–295, 1988 (unpublished).

35. K. G. Hayes et al., Phys. Rev. **D25**, 2869 (1982).

36. K. K. Gan, SLAC–PUB–4530, 1988 (submitted to Phys. Lett. B).

37. We classify the decay $\tau^- \to K^{*-}\nu_\tau \to \pi^- K_s^0 \nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$ as one-charged-particle decay.

38. Gan, Ref. 2.

39. H. Aihara et al., Phys. Rev. Lett. **57**, 1836 (1986).

40. P. R. Burchat et al., Phys. Rev. **D35**, 27 (1987).

41. M. L. Perl, SLAC–PUB–4533, 1988 (submitted to Phys. Rev. D).

42. K. G. Hayes and M. L. Perl, SLAC–PUB–4471, 1988 (submitted to Phys. Rev. D).

43. B_e here is the fitted value of B_e from the measurements of B_e and B_μ together with the assumption of lepton universality.