New Results on Rare τ Decays

K.K. GAN

Department of Physics, The Ohio State University, Columbus, OH 43210, U.S.A.

This is a review of new results on rare decays of the τ lepton. The results include new upper limits on the seven-pion decay $\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau$, and new measurements on the five-pion decay $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and the six-pion decays, $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ and $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$, including the first observation of the decay $\tau^- \to \pi^-\omega 2\pi^0\nu_\tau$. Also included is a review of the first measurement of the Cabibbo-suppressed decay $\tau^- \to K^{*-}\eta\nu_\tau$. The results are compared with the Standard Model predictions, including a detailed comparison of the six-pion decays with isospin symmetry and Conserved-Vector-Current (CVC) expectations.

1. INTRODUCTION

Rare decays of the τ lepton are of particular interest. In rare decays, the Standard Model interaction is suppressed and therefore the sensitivity to new physics may be enhanced. In this paper, we review the new upper limits on the seven-pion decay $\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau$, new measurement of the five-pion decay $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and six-pion decays, $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ and $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$, including the first observation of the decay $\tau^- \to \pi^-\omega 2\pi^0\nu_\tau$. Also included is a review of the first measurement of the Cabibbo-suppressed decay $\tau^- \to K^{*-}\eta\nu_\tau$. The results are compared with the Standard Model predictions, including a detailed comparison of the six-pion decays with isospin symmetry and Conserved-Vector-Current (CVC) expectations. In all the measured branching fractions discussed in this review, the experimenters assume that all charged particles are pions in their measurements unless otherwise specified.

2. SEVEN-PION DECAY

The decay of the τ lepton into final states with seven or more pions [1] is of particular interest since it may provide a sensitive probe of the ν_τ mass due to the limited phase space. The HRS experiment [2] published in 1987 the first upper limit on the branching fraction for the decay into seven charged pions plus any number of neutral particles, $B(\tau^- \to 4\pi^-3\pi^+ \geq 0 \text{ neutrals } \nu_\tau) < 1.9\times10^{-4}$ (All limits quoted are at the 90% confidence level.) There are two new experimental upper limits on the branching fractions. The OPAL experiment [3] has searched for the decay into seven charged particles and zero or one π^0 and set an upper limit on the branching fraction of

$$B(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 1.4\times10^{-5} \ .$$

CLEO II has also searched for the decay [4] and found no evidence of a signal, resulting in a new upper limit on the branching fraction,

$$B(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 2.4\times10^{-6} \ .$$

This limit represents a significant improvement over the OPAL limit. At 90% confidence level, the seven-pion decay therefore occurs in less than 2.4 parts per million, a very suppressed decay indeed. This branching fraction is much smaller than that for the five-pion decay [5] $B(\tau^- \to 3\pi^-2\pi^+(\pi^0)\nu_\tau) \sim 1\times10^{-3}$. There is no theoretical prediction on the branching fraction for the seven-pion decay.

It is of interest to estimate the expected sensitivity on the seven-pion decay in future experiments. The sensitivity can be estimated from the CLEO II analysis. The experiment has a moderately small background ($\sim$3 events). This background is dominated by the hadronic background which can be rejected by requiring a lepton tag or detached vertex. The experiment is therefore not yet background limited and we can expect future experiments to be sensitive to a branching fraction of one part per 10 million for another order of magnitude increase in data sample.

3. FIVE-PION DECAY

The five-pion decay of the τ lepton proceeds through the axial-vector current. The branching fraction has been calculated by Pham, Roiesnel, and Truong [6] using current algebra and Partially-Conserved-Axial-Current (PCAC) hypothesis,

$$B(\tau^- \to (5\pi)^-\nu_\tau) \sim 9 \times 10^{-3} \ .$$

A measurement of the branching fraction allows a test of the prediction.

There is a new measurement of the branching fraction for the five-charged-pion decay by OPAL [7],

$$B(\tau^- \to 3\pi^-2\pi^+\nu_\tau) = (0.91 \pm 0.14 \pm 0.05) \times 10^{-3} \ .$$

This is consistent with the world average compiled by the Particle Data Group [5],

$$B(\tau^- \to 3\pi^-2\pi^+\nu_\tau) = (0.75 \pm 0.07) \times 10^{-3} \ .$$

Combining the two branching fractions yields a new world average of

$$B(\tau^- \to 3\pi^-2\pi^+\nu_\tau) = (0.78 \pm 0.06) \times 10^{-3} \ .$$

This new average branching fraction can be combined with the world average branching fractions [5] for the two other five-pion decays,

$$B(\tau^- \to \pi^-4\pi^0\nu_\tau) = (1.7 \pm 0.6) \times 10^{-3}$$
$$B(\tau^- \to 2\pi^-\pi^+2\pi^0\nu_\tau) = (5.3 \pm 0.4) \times 10^{-3} \ ,$$

to yield a new branching fraction for five-pion decay,

$$B(\tau^- \to (5\pi)^-\nu_\tau) = (7.8 \pm 0.7) \times 10^{-3} \ .$$

The new measurement is therefore consistent with the theoretical expectation. However, the same calculation yields a prediction for $B(\tau^- \to (3\pi)^-\nu_\tau)$ that is a factor of two smaller than the experimental measurement.

It should be noted that even though the spectral function of the five-charged-pion decay has been extensively studied by many experiments measuring the ν_τ mass, there is no published detailed study of the spectral function. Publication of the spectral function will allow experimenters to study the effect of using different spectral functions extracted by various experiments on the ν_τ mass measurement.

4. SIX-PION DECAY

The six-pion decay of the τ lepton proceeds through the vector current. There are three possible six-pion final states, $\tau^- \to \pi^-5\pi^0\nu_\tau$, $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$, and $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$. The branching fractions for the three decays are related by isospin symmetry to four possible isospin states [8], 510 ($4\pi\rho$), 330 (3ρ), 411 ($3\pi\omega$), and 321 ($\pi\rho\omega$), denoted according to the lowest mass states. The branching fractions are also related to the cross section for $e^+e^- \to 6\pi$ by the Conserved-Vector-Current (CVC) hypothesis [9]. The decay can therefore be used to test the isospin and CVC predictions. However, these predictions are for the $I = 1$ component of the hadronic weak vector current so any $I = 0$ contribution to the e^+e^- cross-section or any axial-vector contribution to the τ decay through an η intermediate state must be removed before the comparison. Example of the corrections are the contributions from the $I = 0$ process $e^+e^- \to \eta\pi^+\pi^-\pi^0$ and the axial decay $\tau^- \to 2\pi^-\pi^+\eta\nu_\tau \to 3\pi^-2\pi^+\pi^0\nu_\tau$.

4.1. $\tau^- \to \pi^-5\pi^0\nu_\tau$

The decay $\tau^- \to \pi^-5\pi^0\nu_\tau$ has ten photons in the final state and hence present a major experimental challenge due to the large combinatoric background. The decay has not yet been observed. However, we expect the branching fraction to be small from CVC due to the relatively small measured cross-section for $e^+e^- \to 3\pi^+3\pi^-$ in comparison to other six-pion final states [10].

4.2. $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$

There is a new measurement on the branching fraction for the decay $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ by OPAL [7],

$$B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau) = (2.7 \pm 1.8 \pm 0.7) \times 10^{-4} \ .$$

This is consistent with the world average compiled by the Particle Data Group [5],

$$B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau) = (2.2 \pm 0.5) \times 10^{-4} \ .$$

4.3. $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$

There is an inclusive measurement on the branching fraction for the decay with three charged pions and three or more π^0's by ALEPH [11],

$$B(\tau^- \to 2\pi^-\pi^+ \geq 3\pi^0\nu_\tau) = (11 \pm 4 \pm 5) \times 10^{-4} \ .$$

This is large in comparison to the isospin and CVC expectations as pointed out by in the papers by Sobie [10] and Rouge [12]. The CLEO II experiment [13] has measured the branching fraction by exclusively reconstructing the six photons from the $3\pi^0$ decays. Figure 1 shows the $\gamma\gamma$ invariant mass spectrum, expressed in standard deviations from the nominal π^0 mass,

$$S_{\gamma\gamma} = (m_{\gamma\gamma} - m_{\pi^0})/\sigma_{\gamma\gamma} \ ,$$

where $\sigma_{\gamma\gamma}$ is the mass resolution calculated from the energy and angular resolution of each photon. The three $S_{\gamma\gamma}$ distributions are classified according to the π^0 energy. For each distribution, the $S_{\gamma\gamma}$ of the other two photon pairs must be in their respective π^0 signal regions. An enhancement at zero is evident in all three distributions, corresponding to the observation of the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$. The branching fraction is measured to be

$$B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) = (2.85 \pm 0.56 \pm 0.51) \times 10^{-4} \ .$$

This rate is much smaller than that measured by ALEPH. It should be noted that the CLEO measurement is not used in the 1998 global fit of the τ decay branching fractions by the Particle Data Group. Instead, the inclusive ALEPH result is used, which yields an even higher inclusive branching fraction,

$$B(\tau^- \to 2\pi^-\pi^+ \geq 3\pi^0\nu_\tau) = (14^{+9}_{-7}) \times 10^{-4} \ .$$

The CLEO II experiment has searched for substructure in the $\pi^+\pi^-\pi^0$ system. An ω signal is evident as shown in Fig. 2, corresponding to the first observation of the decay $\tau^- \to \pi^-2\pi^0\omega\nu_\tau$. The branching fraction is measured to be

$$B(\tau^- \to \pi^-2\pi^0\omega\nu_\tau) = (1.89^{+0.74}_{-0.67} \pm 0.40) \times 10^{-4} \ .$$

The small η signal originated from the decay $\tau^- \to \pi^-2\pi^0\eta\nu_\tau$ with $\eta \to \pi^+\pi^-\pi^0$ which has

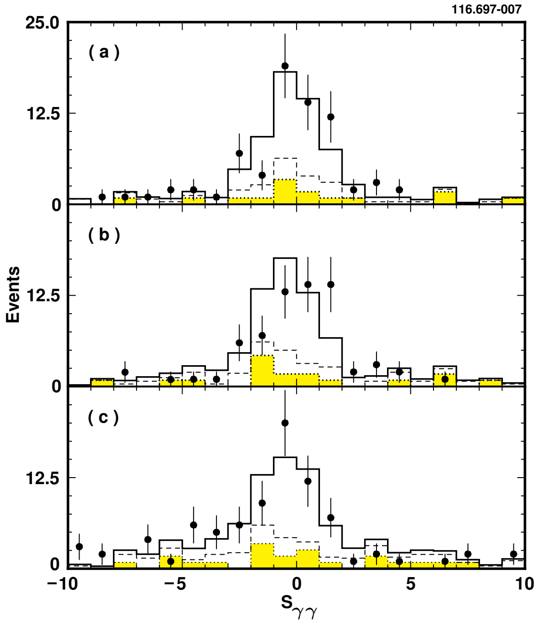

Figure 1. The $S_{\gamma\gamma}$ distribution for the (a) highest, (b) intermediate, and (c) lowest energy π^0 in the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ as measured by the CLEO II experiment. The solid histogram is the sum of the signal Monte Carlo and background (dashed), which includes the τ migration and hadronic (shaded) background.

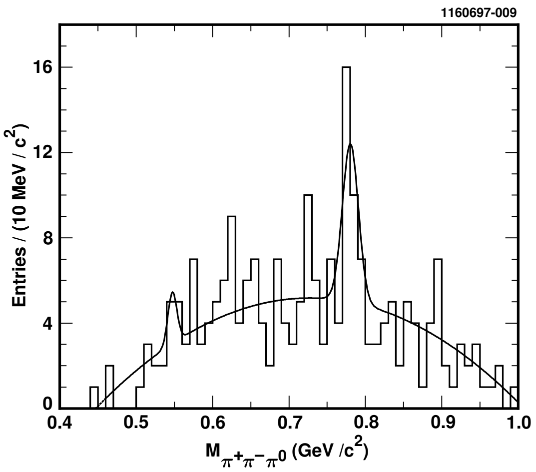

Figure 2. Invariant mass spectrum of $\pi^+\pi^-\pi^0$ combinations in the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ as measured by the CLEO II experiment. The curve shows a fit to the data.

been observed [14] in the decay channel $\eta \to \gamma\gamma$ with much higher statistical significance.

We can test isospin symmetry by comparing the fractions of the $I = 1$ component of the six-pion decay in the $2\pi^+\pi^-3\pi^0$ and $3\pi^+2\pi^-\pi^0$ final states,

$$\mathrm{f}_{2\pi^-\pi^+3\pi^0} = \frac{B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)}{B(\tau^- \to (6\pi)^-\nu_\tau)}$$

$$\mathrm{f}_{3\pi^-2\pi^+\pi^0} = \frac{B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau)}{B(\tau^- \to (6\pi)^-\nu_\tau)} ,$$

where $B(\tau^- \to (6\pi)^-\nu_\tau)$ is the sum of the three branching fractions,

$$\begin{aligned} B(\tau^- \to (6\pi)^-\nu_\tau) = {} & B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) \\ & + B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau) \\ & + B(\tau^- \to \pi^-5\pi^0\nu_\tau) \ . \end{aligned}$$

Since $B(\tau^- \to \pi^-5\pi^0\nu_\tau)$ has not yet been measured, the measurement can only be presented as a line through the origin in the $\mathrm{f}_{2\pi^-\pi^+3\pi^0}$ vs. $\mathrm{f}_{3\pi^-2\pi^+\pi^0}$ plot:

$$\mathrm{f}_{2\pi^-\pi^+3\pi^0} = \frac{B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)}{B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau)} \times \mathrm{f}_{3\pi^-2\pi^+\pi^0}.$$

Sobie [10] and Rouge [12] had performed an isospin analysis of these decays and concluded that there was a discrepancy between the measured decay branching fractions and the isospin expectation. However, the authors did not correct for the axial-vector contributions from the decays $\tau^- \to 2\pi^-\pi^+\eta\nu_\tau$ and $\pi^-2\pi^0\eta\nu_\tau$. The CLEO II experiment used their measurement of $B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ and the world average measurement of $B(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau)$ [5] to test isospin symmetry. The experiment corrected for the axial-vector contributions using their own measurements [14] of the branching fractions,

$$B(\tau^- \to 2\pi^-\pi^+\eta\nu_\tau) = (3.5^{+0.7}_{-0.6} \pm 0.7) \times 10^{-4}$$

$$B(\tau^- \to \pi^-2\pi^0\eta\nu_\tau) = (1.4 \pm 0.6 \pm 0.3) \times 10^{-4} \ .$$

The former decay contributes to the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ via the decay channel $\eta \to 3\pi^0$ while the latter contributes via the decay $\eta \to \pi^+\pi^-\pi^0$. The former decay also contributes to the decay $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ via the decay channel $\eta \to \pi^+\pi^-\pi^0$. Correcting for axial-vector contributions yields the six-pion branching fractions for the vector decays,

$$B_V(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) = (1.41 \pm 0.76) \times 10^{-4}$$

$$B_V(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau) = (1.39 \pm 0.55) \times 10^{-4} \ .$$

The experimental measurement based on these branching fractions is shown as a line in the $\mathrm{f}_{2\pi^-\pi^+3\pi^0}$ vs. $\mathrm{f}_{3\pi^-2\pi^+\pi^0}$ plot in Fig. 3. The line is terminated by the unitarity bound,

$$\mathrm{f}_{2\pi^-\pi^+3\pi^0} + \mathrm{f}_{3\pi^-2\pi^+\pi^0} \leq 1 \ .$$

Including one standard deviation of the experimental uncertainty, the experimentally allowed region becomes a triangle. Also shown is the isospin predictions for the four isospin states, which form a theoretically allowed triangular region. There is some overlap between the two triangles, consistent with the isospin symmetry expectation.

It is evident by comparing $B(\tau^- \to \pi^-2\pi^0\omega\nu_\tau)$ and $B_V(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ that the η and ω intermediate states saturate the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$. We can therefore also test the

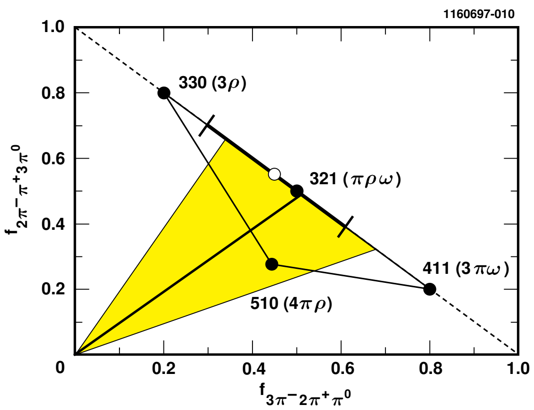

Figure 3. $f_{2\pi^-\pi^+3\pi^0}$ vs. $f_{3\pi^-2\pi^+\pi^0}$. The solid line from the origin uses the CLEO II result on $B_V(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ and the world average measurement of $B_V(\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau)$ (see text). The shaded area indicates the one standard deviation region. The open circle with diagonal error bar [15] uses the CLEO II measurement of $B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ from the decay $\tau^- \to \pi^-2\pi^0\omega\nu_\tau$ together with the assumption that $B(\tau^- \to \pi^-5\pi^0\nu_\tau) = 0$. The triangular region indicates the isospin expectation. Unitarity requires the fractions to be below the dashed line.

isospin prediction by using $B(\tau^- \to \pi^-2\pi^0\omega\nu_\tau)$ as a measurement of the vector component of $B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$. Using the decay branching fraction [5] $B(\omega \to \pi^+\pi^-\pi^0) = (88.8 \pm 0.7)\%$, the measurement of $B(\tau^- \to \pi^-2\pi^0\omega\nu_\tau)$ yields the following $3\pi3\pi^0$ decay branching fraction,

$$B_\omega(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) = (1.68 \pm 0.72) \times 10^{-4} .$$

With the assumption that $B(\tau^- \to \pi^-5\pi^0\nu_\tau)$ is negligible, this measurement is consistent with the isospin expectation as shown in Fig. 3. The result prefers the dominance of the [321] ($\pi\rho\omega$) isospin state over the [411] ($3\pi\omega$) state. However, the CLEO II experiment is not able to distinguish the two states from the observed $\pi\pi^0$ mass spectrum.

The measurements of $B_V(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ and $B_\omega(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau)$ can also be compared with the CVC predictions by Sobie [10],

$$B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) = (1.9 - 7.3) \times 10^{-4} ,$$

and Eidelman [16],

$$B(\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau) = (2.5 \pm 0.4) \times 10^{-4} .$$

The result is somewhat below the predictions, indicating that there could be a substantial $I = 0$ contribution from $e^+e^- \to \eta\pi^+\pi^-\pi^0$ to $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ that must be removed before calculating the CVC predictions.

5. CABIBBO-SUPPRESSED DECAY $\tau^- \to K^{*-}\eta\nu_\tau$

The study of the hadronic decays of the τ lepton is important for a better understanding of the weak hadronic current and its symmetries. The decays involving an η meson are associated with the Wess-Zumino-Witten anomaly [17] and are rare. The first such decay, $\tau^- \to \pi^-\pi^0\eta\nu_\tau$, was observed by CLEO II in 1992 [18] and subsequently by ALEPH [19]. More recently, CLEO II has measured the branching fractions of two other decays [20][14],

$$B(\tau^- \to K^-\eta\nu_\tau) = (2.6 \pm 0.5 \pm 0.5) \times 10^{-4}$$

$$B(\tau^- \to (3h)^-\eta\nu_\tau) = (3.5^{+0.7}_{-0.6} \pm 0.7) \times 10^{-4} ,$$

where h can either be a π or K. Both measurements are two orders of magnitude higher than the predictions by Pich [21] based on chiral perturbation theory. However, the recent calculation by Li [22] using an effective chiral theory in the limit of chiral symmetry is in good agreement with these results. In the calculation, the former decay proceeds through the vector current with K^* dominant and the latter decay proceeds through the axial-vector current with a_1 dominant.

Pich and Li have also calculated the branching fractions for the decay $\tau^- \to (K\pi)^-\eta\nu_\tau$. Pich predicts the branching fractions to be

$$B(\tau^- \to K^-\pi^0\eta\nu_\tau) \sim 8.8 \times 10^{-6}$$

$$B(\tau^- \to \pi^-\bar{K^0}\eta\nu_\tau) \sim 2.2 \times 10^{-5} ,$$

with K^* enhancement of the $K\pi$ rate. Li predicts that the ηK^* final state is produced via the axial-vector current, with the spectral function dominated by the K_1 resonance, giving

$$B(\tau^- \to K^{*-}\eta\nu_\tau) = 1.01 \times 10^{-4} .$$

The CLEO II experiment [23] has observed the decay $\tau^- \to K^{*-}\eta\nu_\tau$, with $K^{*-} \to K^-\pi^0$ and $K^{*-} \to K_S\pi^- \to \pi^-\pi^+\pi^-$. The η signal is reconstructed using the $\gamma\gamma$ decay channel. As an example of the analysis, Fig. 4 shows the invariant mass spectra of two photons accompanying the K_S candidate. An η signal is observed in the K^{*-} signal region, and there is no indication of a signal in the sideband region. As a check of the validity of the signal, the experiment examines the invariant mass spectrum of the $K_S\pi^-$ system for events with an η candidate. A clear K^{*-} signal is observed as shown in Fig. 5. The experiment has therefore observed for the first time the decay $\tau^- \to K^{*-}\eta\nu_\tau$. The branching fractions extracted are

$$B(\tau^- \to K^{*-}\eta\nu_\tau) \times B(K^{*-} \to K_S\pi^-) = (1.18 \pm 0.38 \pm 0.12) \times 10^{-4}$$

$$B(\tau^- \to K^{*-}\eta\nu_\tau) \times B(K^{*-} \to K^-\pi^0) = (0.69 \pm 0.36 \pm 0.28) \times 10^{-4} .$$

Since isospin symmetry requires

$$B(K^{*-} \to K_S\pi^-) = B(K^{*-} \to K^-\pi^0) = \frac{1}{3} ,$$

the two measurements are consistent with each other given the large errors. Combining these results assuming isospin symmetry yields

$$B(\tau^- \to K^{*-}\eta\nu_\tau) = (2.90 \pm 0.80 \pm 0.42) \times 10^{-4} .$$

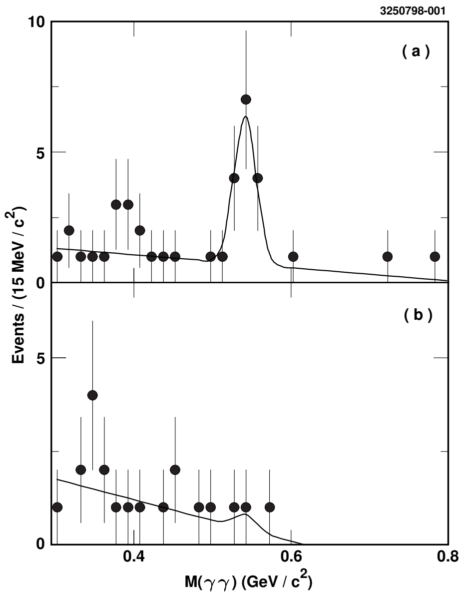

Figure 4. The invariant mass spectrum of the photon pairs in the signal hemisphere containing a K_S candidate as measured by the CLEO II experiment. The $K_S\pi^-$ invariant mass is required to be in the K^{*-} signal band in (a) and in the K^{*-} sideband in (b). The curves show fits to the data.

The CLEO II experiment has also measured the inclusive branching fraction without requiring the K^* resonance. The inclusive measurements are

$$B(\tau^- \to K_S\pi^-\eta\nu_\tau) = (1.10 \pm 0.35 \pm 0.11) \times 10^{-4}$$

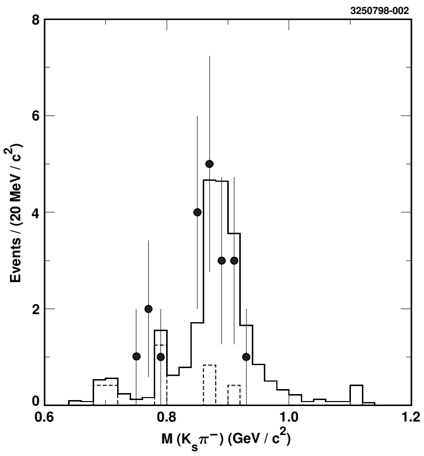

Figure 5. The invariant mass spectrum of the $K_S\pi^-$ system in the signal hemisphere containing an η candidate as measured by the CLEO II experiment. The histograms show the Monte Carlo expectation, including the hadronic background (dotted).

$$B(\tau^- \to K^-\pi^0\eta\nu_\tau) = (1.77\pm0.56\pm0.71)\times10^{-4}\,.$$

The inclusive results are in reasonable agreement with the measurements requiring the K^* resonance.

The CLEO II experiment has therefore measured for the first time the branching fraction of $\tau^- \to K^{*-}\eta\nu_\tau$. The result is somewhat higher than the theoretical prediction by Li [22] (1.01×10^{-4}). The inclusive branching fractions without requiring the K^* resonance have also been measured. The measurements are significantly higher than the theoretical predictions by Pich [21]. The results for the $\tau^- \to K_S\pi^-\eta\nu_\tau$ mode indicate that the K^{*-} resonance dominates the $K_S\pi^-$ mass spectrum.

6. Conclusion

In conclusion, there are several new results on rare decays of the τ lepton. The branching fraction for the seven-pion decay $\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau$ has been measured to be less than 2.4 parts per million at 90% confidence level. The measured branching fraction for the five-pion decay is consistent with the theoretical expectation based on current algebra and PCAC. The exclusive branching fraction for the six-pion decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ has been measured, resolving a long standing discrepancy with isospin symmetry. However, the measurement is somewhat below the CVC predictions based on the measured cross section for $e^+e^- \to 6\pi$, indicating that there could be a substantial $I=0$ contamination in the e^+e^- cross section. The decay $\tau^- \to \pi^-\omega2\pi^0\nu_\tau$ has been observed for the first time. The measured branching fraction indicates that the decay $\tau^- \to 2\pi^-\pi^+3\pi^0\nu_\tau$ proceeds exclusively through the η and ω intermediate states. The Cabibbo-suppressed decay $\tau^- \to K^{*-}\eta\nu_\tau$ has also been observed. The result is somewhat higher than the theoretical prediction. The inclusive branching fractions without requiring the K^* resonance have also been measured. The measurements are significantly higher than the theoretical predictions. The results indicate that the K^* resonance saturates the inclusive decays.

Acknowledgments

This work was supported in part the U.S. Department of Energy. The author wishes to thank J. Duboscq for the careful reading of this manuscript and the organizers for the wonderful meeting.

REFERENCES

1. Phase space consideration limits the number of pions in τ decay to twelve or less.
2. B.G. Bylsma *et al.*, Phys. Rev. D **35**, 2269 (1987).
3. K. Ackerstaff *et al.*, Phys. Lett. B **404**, 213 (1997).
4. K. W. Edwards *et al.*, Phys. Rev. D. **56**, 5297 (1997).
5. Particle Data Group, C. Caso *et al.*, Review of Particle Properties, Eur. Phys. J. C **3**, 1, (1998).
6. T.N. Pham, C. Roiesnel, and T.N. Truong, Phys. Lett. B **78**, 623 (1978).
7. K. Ackerstaff *et al.*, CERN-EP/98-090, 1998 (submitted to Eur. Phys. J.)

8. A. Pais, Ann. Phys. **9**, 548 (1960). For an isospin state $[n_1, n_2, n_3]$, n_3 is the number of subsystems of three pions with $I = 0$, $n_2 - n_3$ is the number of subsystems of two pions with $I = 1$, and $n_1 - n_2$ is the number of remaining single pions.
9. R.P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
10. R.J. Sobie, Z. Phys. C **69**, 99 (1995).
11. D. Buskulic *et al.*, Z. Phys. C **70**, 579 (1996).
12. A. Rouge, Z. Phys. C **70**, 65 (1996).
13. S. Anderson *et al.*, Phys. Rev. Lett. **79**, 3814, 1997.
14. T. Bergfeld *et al.*, Phys. Rev. Lett. **79**, 2406 (1997).
15. The error bar is along the diagonal line because of the unitarity assumption,

$$\mathrm{f}_{2\pi^-\pi^+3\pi^0} + \mathrm{f}_{3\pi^-2\pi^+\pi^0} = 1 \ .$$

16. S.I. Eidelman and V.N. Ivanchenko, Nucl. Phys. B (Proc. Suppl.) **55C**, 181 (1997). (Proceedings of the Fourth International Workshop on Tau Lepton Physics, Estes Park, Colorado, 1996, edited by J.G. Smith and W. Toki.)
17. J. Wess and B. Zumino, Phys. Lett. B **37**, 95 (1971); E. Witten, Nucl. Phys. B **223**, 422 (1983).
18. CLEO Collaboration, M. Artuso *et al.*, Phys. Rev. Lett. **69**, 3278 (1992).
19. ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. C **74**, 263 (1997).
20. CLEO Collaboration, J. Bartelt *et al.*, Phys. Rev. Lett. **76**, 4119 (1996).
21. A. Pich, Phys. Lett. B **196**, 561 (1987).
22. B. A. Li, Phys. Rev. D **55**, 1436 (1997); Phys. Rev. D **57**, 1790 (1998).
23. M. Bishai *et al.*, CLNS 98/1574, 1998 (to be published in Phys. Rev. Lett.)