NEW τ PHYSICS FROM PEP

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1. INTRODUCTION

After the discovery of the τ lepton at SLAC many of its properties were studied in e^+e^- annihilation at SPEAR and DORIS.[1] More recently, the high statistics data samples obtained at higher energies from PEP and PETRA have added considerable information. The signature of the τ pair production is very distinct at energies well above the threshold. In particular, the clear difference between the shapes of $\tau^+\tau^-$ and hadronic events opened new possibilities to study the hadronic decays of the τ. The improvement is most striking for its multiprong decays which have been used,e.g.,to set new limits on the τ neutrino mass (Sect. 6).

In the standard model the τ is a sequential lepton with the same interactions as the μ and the electron. This lepton universality has been tested at SPEAR and DORIS mainly with the purely leptonic decays of the τ into electron or μ and with the semileptonic decays into π (Sect. 3.2 and Ref. [1]). Recently, the precise measurement of the Cabibbo suppressed decay $\tau \to K\nu$ (Sect. 3.2) and the determination of the τ lifetime[2] have filled the two major gaps in the confirmation of the τ–μ–e universality left by the experiments at lower energies.

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The τ is the only lepton sufficiently massive to decay into hadrons. This makes it an ideal tool to study hadronic weak interactions under simple conditions. In the standard picture its hadronic decays are expected to be dominated by two-body decays into a resonance and the neutrino and the individual branching ratios are predicted from CVC, PCAC and sum-rules (Sect. 4.1). With the new measurements submitted to this conference (Sect. 4.3) the branching ratios of all decays predicted in the standard picture can be now determined.

Since all we know about the τ lepton is based on results obtained at e^+e^- storage rings I will concentrate on this type of experiment. Other possible measurements with the τ or its neutrino are outlined in the previous review by M.Perl.[1]

2. EVENT SELECTION AT PEP AND PETRA

The charged multiplicity of τ decays is very low: about 87% of the decays result in one charged particle and about 13% in 3 prongs. Decays into more than 3 charged particles are not, as yet, observed. Since the mass of the τ (1784.2±3.2 MeV/c^2) is small compared with the beam energies at PEP and PETRA the events are characterized by two back-to-back jets of particles with low multiplicity and, for multiprong jets, low invariant mass. Most of the available energy is detected either in charged tracks or in π°. The selection of events with such shape rejects the high-multiplicity hadronic events and the events from the two photon process where only a small fraction of the beam energy is visible in the detectors. The dominant remaining background, due to QED processes, is reduced by acolinearity cuts on events with 2 charged tracks.

The filtered events have three distinct topologies, characterized by the number of tracks in each hemisphere:

- 1-3 topology: Where one of the τ's decays into one charged particle and the other into three. The contribution to this topology from sources other than τ pair production at PEP/PETRA energies is very small. The reaction $e^+e^- \to q\bar{q}$ leads only rarely to low multiplicity events and radiative QED processes with photon conversions are easily removed. Although the efficiency of the experimental cuts is quite high, the number of events in selected samples of this topology is limited because of the relatively small branching ratio of the τ into three prongs.
- 1-1 topology: Here QED processes present the dominant background. Some restrictions to specific τ decay modes are necessary, e.g. events with two identified electrons or muons are usually not accepted because of the difficulty in separating them from Bhabha scattering or μ pair production.
- 3-3 topology: Only about 2% of the τ-pairs fall into this topology and hadronic events are a serious background. Therefore the data are used for very special purposes only, e.g. the measurement of the charged multiplicity of τ decays.

3. LEPTON UNIVERSALITY

The basic properties of the τ have already been explored at SPEAR and DORIS. We know from the measurement of the cross section for $e^+e^- \to \tau^+\tau^-$, the study of the decays $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$ and $\tau \to \pi\nu$ and stringent limits on the branching ratios of rare decays like $\tau \to e\gamma$ that the τ has spin 1/2 and does not interact through the strong interactions.[1] All results are consistent with the standard model in which the τ is the third sequential lepton with its own conserved lepton number and a unique associated neutrino. It cannot be an ortholepton nor a paralepton, i.e. a lepton with the same lepton number as the electron or as the μ.[1]

If the τ is really a sequential lepton, as I will assume from now on, the question of the lepton universality can be addressed: Do the three charged leptons e, μ and τ have the same interactions? There are two different possibilities for a violation of the lepton universality:

(1) The leptons couple to the same V-A current but with different coupling constants or

3.2 Charged Current: Decays

The four simple τ decays illustrated in Fig. 1 are used to test τ–μ universality. The rates for these decays can be calculated in a model independent way since the coupling constants are measured in corresponding decays involving a μ (see right side of Fig. 1). As a typical example the τ decay rate into a π is derived from the π decay rate into $\mu\nu$.

The Lagrangian for the graph, Fig. 1d, has to be written in a form that allows violation of lepton universality:

$$L = \frac{G}{\sqrt{2}} \left[g_d g_l (\bar{u}\Gamma d)(\bar{l}\Gamma \nu) + g_d' g_l' (\bar{u}\Gamma' d)(\bar{l}\Gamma' \nu) \right] . \tag{4}$$

Here, the first term is due to the normal weak V-A current and the second one is due to possible additional interactions. The subscript l in the coupling constants stands for the coupling to lepton-neutrino and d for the coupling to a $u\bar{d}$ quark pair. The corresponding coupling constant to $u\bar{s}$ will be called g_s. The coupling constants are given in the standard model:

$$\begin{matrix} g_d = \cos\theta_c \\ g_s = \sin\theta_c \end{matrix} \qquad g_l = 1 \qquad g_d' = g_l' = 0 . \tag{5}$$

To simplify the formulae, I will concentrate on additional interactions mediated by a spin 1 boson. Then the decay rate of Fig. 1d can be written as[5]

$$\Gamma(\tau \to \pi\nu) = \frac{G^2 f_\pi^2}{8\pi} (g_d g_\tau + g_d' g_\tau')^2 m_\tau^3 \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 . \tag{6}$$

The pion decay constant f_π describes the details of the vertex in the Fig. 1d where the intermediate boson couples to a π. The calculation has to rely on nonperturbative QCD and is extremely model dependent. However, the corresponding π decay (Fig. 1e) probes exactly the same vertex. The rate for this decay is

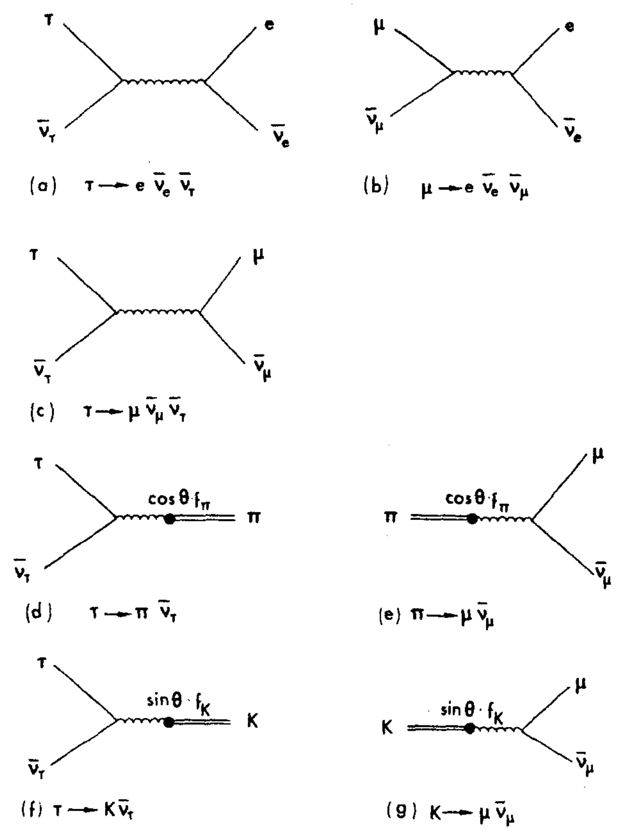

Fig. 1 The diagrams for simple τ decays and the corresponding μ, π and K decays.

TABLE 2

Measurements of τ Branching Ratios

Quantity	Result	Reference
$BR(\tau \to e\nu\nu)$	.190 ± .090	[6]
$BR(\tau \to e\nu\nu)$	.183 ± .031	[7]
$BR(\tau \to \mu\nu\nu)$	.35 ± .14	[6]
$BR(\tau \to \mu\nu\nu)$	.178 ± .027	[8]
$BR(\tau \to \mu\nu\nu)$	.176 ± .033	[9]
$BR(\tau \to \mu\nu\nu) \times BR(\tau \to e\nu\nu)$	.034 ± .009	[9]
$BR(\tau \to \mu\nu\nu) \times BR(\tau \to e\nu\nu)$	.030 ± .005	[10]
$BR(\tau \to e\nu\nu)/BR(\tau \to \mu\nu\nu)$	1.09 ± .38	[11]
$BR(\tau \to \pi\nu)$	.099 ± .021	[7]
$BR(\tau \to \pi\nu) \times BR(\tau \to e\nu\nu)$	.013 ± .006	[9]
$BR(\tau \to \pi\nu) \times BR(\tau \to e\nu\nu)$	.018 ± .004	[10]
$BR(\tau \to \pi\nu) \times BR(\tau \to \mu\nu\nu)$	.024 ± .006	[10]
$BR(\tau \to \rho\nu)$	.220 ± .021	Sect. 4.2
$BR(\tau \to \rho\nu)$	.221 ± .025	[7]
$BR(\tau \to \rho\nu) \times BR(\tau \to e\nu\nu)$	.034 ± .008	[12]
$BR(\tau \to \rho\nu) \times BR(\tau \to \mu\nu\nu)$	.041 ± .009	[12]
$BR(\tau \to XXX + n\pi^\circ + \nu)/BR(\tau \to 3\ \text{prong})$	.48 ± .06	Sect. 4.3.2
$BR(\tau \to 3\ \text{prong})$	.136 ± .006	Sect. 4.3.1
$BR(\tau \to K\nu)$	.0059 ± .0018	[13]
$BR(\tau \to K\nu)$	0.13 ± .005	[14]
$BR(\tau \to K^{*}\nu)$	.0150 ± .0036	Sect. 4.2
$BR(\tau \to K + n\pi^\circ + \nu)$	.0171 ± .0029	[13]
$BR(\tau \to K\pi\pi(\pi^\circ)\nu)$	.0022 ± .0015	Sect. 4.3.3
$BR(\tau \to KK\pi\nu)$	.0022 ± .0015	Sect. 4.3.3
τ_τ	$(2.97 \pm .25) + 10^{-13}$ sec	[2]

The best use of available data is made by fitting the electron branching ratio with the ratios (13) fixed to their expected values. The result is

$$BR(\tau \to e\nu\nu) = 17.60 \pm 0.78\% \tag{14a}$$

and with the τ lifetime (12) one finds the ratio

$$\frac{g_\tau}{g_\mu} = 0.974 \pm 0.045 \ . \tag{15a}$$

This ratio can be deduced also under slightly weaker assumptions on additional interactions using the two purely leptonic decays shown in Fig. 1a and 1b. In this case the only assumption is that the additional coupling to the electron, g_e', is small. The fit of three independent branching ratios to the same 13 entries in Table 2 yields

$$\begin{aligned} BR(\tau \to e\nu\nu) &= 17.2 \pm 1.8\%\,, \\ BR(\tau \to \mu\nu\nu) &= 18.3 \pm 1.7\%, \\ BR(\tau \to \pi\nu) &= 10.1 \pm 1.4\%, \end{aligned} \tag{14b}$$

and the ratio of the weak coupling constants becomes

$$\frac{g_\tau}{g_\mu} = 0.926 \pm 0.062 \ . \tag{15b}$$

Thus the weak coupling constant of the τ and the μ are equal within the experimental uncertainties of 5%. The analogous test for the electron and the μ coupling uses the π decays into electron and muon. The most recent experiment[16] finds equal couplings to a precision of 0.6%. Therefore, all present measurements support the universality of the weak coupling constant.

3.2.2 Additional Interactions

Over the past few years the search for interactions beyond the electroweak interactions has become increasingly attractive. Many models attempting to unify the known interactions have been proposed based on grand unified or supersymmetric theories. Most of these models predict the existence of additional "superweak" interactions. The couplings of these new interactions can be different for fermions of different generations, e.g. through mixing matrices or mass dependent coupling constants. Therefore it is important to search for and to set limits on such new interactions.

Best sensitivity to new interactions is obtained in the study of highly suppressed decays. The DELCO group has measured recently the branching ratio of the Cabibbo suppressed decay $\tau \to K\nu$.[13] The experiment provides very clean kaon identification using a large solid angle Čerenkov counter. There are 21 τ events found with a single prong kaon and no neutral energy in a cone of ±45 degrees around the kaon track. These events are due to $\tau \to K\nu$. The resulting decay branching ratio of τ into a single kaon

$$BR(\tau \to K\nu) = 0.59 \pm 0.18\%$$

provides a substantial improvement over the previous Mark II/SPEAR result[14] of 1.3±0.5% where this decay has first been observed. The weighted average of the two measurements is

$$BR(\tau \to K\nu) = 0.67 \pm 0.17\% \ . \tag{16}$$

Combined with the τ lifetime (12) and the decay width of $K \to \mu\nu$[15] one gets the limits on the coupling constants of new interactions shown in Table 3. Also listed in this table are the corresponding limits obtained from the τ decays into electron and pion. The latest results on muon-electron universality are also included. These come from the comparison of the decay rates of the kaon (or pion) into electron and muon. No evidence for a new interaction violating the lepton universality has been found. As can be seen from the table, the best limits on such interactions come from decays involving pseudoscalar mesons. These decays, however, probe only the axial-vector part of additional interactions. The interpretation of decays into vector mesons is model-dependent (see Sect. 4.1). Therefore the purely leptonic decays have to be used to put limits on vector type interactions.

In conclusion no indication for a violation of the lepton universality has been found. If interactions with different couplings to e, μ and τ exist the coupling constants can be at most a few percent of the Fermi coupling. In the remaining sections I will therefore assume that the τ couples only to the electroweak current and use it as a tool to study hadronic weak interactions.

TABLE 3

Limits on Coupling Constants of New Interactions in Units of the Fermi Coupling

(for definitions and references, see Sect. 3.2 and Eq. (6))

Decays	Limit
$\frac{\Gamma(\tau \to e\nu\nu)}{\Gamma(\mu \to e\nu\nu)}$	$g_e'(g_\tau' - g_\mu') < .206$
$\frac{\Gamma(\tau \to \pi\nu)}{\Gamma(\pi \to \mu\nu)}$	$g_d'(g_\tau' - g_\mu') < .173$
$\frac{\Gamma(\tau \to K\nu)}{\Gamma(K \to \mu nu)}$	$g_s'(g_\tau' - g_\mu') < .055$
$\frac{\Gamma(\tau \to e\nu)}{\Gamma(\pi \to \mu\nu)}$	$g_d'(g_\mu' - g_e') < .016$
$\frac{\Gamma(K \to e\nu)}{\Gamma(K \to \mu\nu)}$	$g_s'(g_\mu' - g_e') < .012$

4. HADRONIC WEAK INTERACTIONS: DECAYS INTO RESONANCES

4.1 Theoretical Framework

The decay rate of the τ into a hadronic final state H with spin 1 can be written as [5]:

$$\Gamma(\tau \to H\nu) = \frac{G^2}{(2\pi)^2(2m_\tau)^2} \int_0^{m_\tau^2} dq^2 (m_\tau^2 - q^2)^2 (m_\tau^2 + 2q^2) \tag{17}$$

$$\cdot \{\cos^2\theta_c [v(q^2) + a(q^2)] + \sin^2\theta_c [v^s(q^2) + a^s(q^2)]\} \ .$$

The first part of this expression comes from the leptonic part of the V-A matrix element and from phase space. The second one with the spectral functions v, a, v^s and a^s describes the hadronic weak current. The notation follows the paper by Y. S. Tsai.[5] The four spectral functions have different quantum numbers and are expected to be dominated by resonances (see Table 4).

TABLE 4

Quantum Numbers of the Spectral Functions

Spectral Function	J	I	G	S	Resonances
$v(q^2)$	1	1	+	0	ρ (770), ρ′ (1600)
$a(q^2)$	1	1	-	0	A(1270)
$v(q^2)$	1	1/2		1	K^*(892)
$a(q^2)$	1	1/2		1	Q(1280), Q(1400)

Firm predictions are possible only for $v(q^2)$. The CVC theorem relates the vector part of the charged weak current to the isovector part of the electromagnetic interactions which is measured in the reaction $e^+e^- \to$ hadrons:

$$v(q^2) = \frac{q^2 \sigma_{I=1}(e^+e^- \to H)}{4\pi\alpha^2} \ . \tag{18}$$

The isolation of the isovector part from the measured e^+e^- cross section requires model dependent assumptions. For example in the case of the ρ, the ρ–ω interference has to be taken into account.

For all other spectral functions listed in Table 4 no corresponding measurable quantity exists which could be used to calculate the τ decay rates. Theoretical predictions have to rely on PCAC and current algebra. Some calculations exist for specific decays only.[17] A more general approach is to use sum rules. Under the assumption of an exact SU(3)×SU(3) symmetry, the masses of the resonances listed in Table 4 would be degenerate and the four spectral functions would be equal. In the case of broken symmetry, some relations between the various spectral functions can be derived such as the Weinberg[18] or the Das-Mathur-Okubo[19] sum rules. In our notation they read [5]:

Weinberg

$$\int_0^\infty [v(q^2) - a(q^2)]\, dq^2 = 2\pi f_\pi^2$$

$$\int_0^\infty q^2 [v(q^2) - a(q^2)]\, dq^2 = 0$$

Das-Mathur-Okubo

$$\int_0^\infty [v^s(q^2) - a^s(q^2)]\, dq^2 = f_K$$

$$\int_0^\infty q^2 [v^s(q^2) - a^s(q^2)]\, dq^2 = 0 \tag{19}$$

$$\int_0^\infty [v(q^2) - v^s(q^2)]\, dq^2 = 0 \ .$$

As an example, consider the τ decay into K^*. In the narrow width approximation the decay rate can be written as

$$\Gamma(\tau \to K^*\nu) = \frac{G^2 \sin\theta_c f_{K^*}^2}{16\pi} \cdot \frac{m_\tau^3}{m_{K^*}^2} \left(1 - \frac{m_{K^*}^2}{m_\tau^2}\right)^2 \left(1 + \frac{2m_{K^*}^2}{m_\tau^2}\right) , \tag{20}$$

where f_{K^*} is the K^* decay constant. The last Das-Mathur-Okubo sum rule relates it to the ρ decay constant. In order to get this relation one has to assume that the difference $v(q^2)-v^s(q^2)$ is dominated by K^* and ρ channels, i.e. that the contributions from higher mass resonances cancel in the difference. This is true if the SU(3) symmetry becomes exact at high masses. Under this assumption we can write

$$v(q^2) = 2\pi \frac{f_\rho^2}{m_\rho^2}\,\delta(q^2 - m_\rho^2)\,, \qquad v^s(q^2) = 2\pi \frac{f_{K^*}^2}{m_{K^*}^2}\,\delta(q^2 - m_{K^*}^2) \tag{21}$$

and the sum rule predicts

$$\frac{f_\rho^2}{m_\rho^2} = \frac{f_{K^*}^2}{m_{K^*}^2}\;. \tag{22}$$

Thus the decay rate of the τ into K^* is related to the rate of the τ decay into ρ. The other sum rules lead to similar relations between the decay constants and masses of the resonances.[5]

In principle a formula similar to Eq. (17) can be written for the decays into spin 0 final states.[5] The corresponding spectral functions are restricted, however, by CVC and PCAC:

$$v_0(q^2) = 0 \qquad \text{CVC}, \qquad a_0(q^2) = 0 \quad \text{for} \quad q^2 >> m_\pi^2 \qquad \text{PCAC}\;. \tag{23}$$

Also the strange spectral functions for spin 0 are negligible compared with the spin 1 spectral functions if SU(3)×SU(3) becomes an exact symmetry at $q^2 > m_K^2$.

The τ is an ideal instrument to study the hadronic weak interactions in very clean conditions. This is reflected in the simplicity of the formulae given in this short theoretical outline. Measurements of τ decay rates can test CVC or, by testing sum rules, provide information about the breaking of the SU(3) symmetry.

4.2 Decays into ρ and K^*

The decay $\tau \to \rho\nu$ is the simplest of the τ decays mediated by the vector part of the weak interactions. In order to predict the rate from the cross section of $e^+e^- \to \pi^+\pi^-$ the ρ–ω interference has to be taken into account. Since the interference in e^+e^- annihilation is due to the G-parity violating mixing of the two resonances, it changes the predicted τ decay rate only by a small amount. The ρ provides therefore a clean test of the CVC theorem.

The Mark II group has remeasured the branching ratios of the τ decays into ρ and the corresponding Cabibbo suppressed decay into K^*. The ρ analysis uses events of the 1-1 and 1-3 topologies. In single prong jets the ρ mass is reconstructed from a charged and a neutral π. The π° are either reconstructed from two well separated photons or measured as one high energy cluster in the calorimeter. Jets with more than 2 clusters in the calorimeter are rejected. The preliminary result,

$$BR(\tau \to \rho\nu) = (22.0 \pm 0.8 \pm 1.9)\% \tag{24}$$

represents the most accurate measurement of this branching ratio so far. The systematic error is dominated by the uncertainty in the identification of photons in the calorimeter. The branching ratio is in excellent agreement with the previous results (Table 2) as well as with the CVC prediction [20]:

$$BR(\tau \to \rho\nu) = 22.1 \pm 2.3\% \tag{25}$$

where the error reflects only the experimental uncertainty of the annihilation cross section.[21] Hence CVC is tested at the 15% level in an almost model independent way.

The K^*'s are found in the 3-prong decays[22]

$$\tau^- \to K^{*-}\nu, \quad K^{*-} \to K^\circ_s \pi^-, \quad K^\circ_s \to \pi^+\pi^-\;.$$

Events in the 1-3 and the 3-3 topology are accepted for this analysis. Two of the three charged tracks have to fit a K° hypothesis with a vertex well separated from the beams and with an appropriate invariant mass. The identified K° is then combined with the third track in the jet. The K^* is defined by the requirement that the invariant mass lies in a window between 800 and 1000 MeV/c^2. Events with detected photons on the K^* side are rejected. With these selections, 28 events are found. The resulting branching ratio

$$BR(\tau \rightarrow K^*\nu) = 1.5 \pm 0.3 \pm 0.2\% \tag{26}$$

has much smaller systematic uncertainties than the previous measurement[23] at SPEAR because of the cleaner environment for multiprong decays at higher energies.

As shown in the previous section the ratio of the two branching fractions is predicted by the Das-Mathur-Okubo sum rules. The experiment is in fair agreement with this prediction:

$$\frac{BR(\tau \rightarrow K^*\nu)}{BR(\tau \rightarrow \rho\nu)} = \begin{cases} 0.068 \pm 0.0014 \pm 0.009 & \text{(experiment)} \\ 0.047 & \text{(sum rules)} \end{cases} \tag{27}$$

This study of the K^* decay has neglected the contamination from the decay chain $\tau \rightarrow \rho'(1600)\nu \rightarrow K^*K^\circ_L\nu$ where the K°_L remains undetected. Its contribution to the branching ratio (26) can be estimated from the recent DELCO measurement[24] of kaons in multiprong decays as 0.2±0.1%. The subtraction from the measured branching ratio (26) improves the agreement between experiment and theory slightly.

If one disregards the model dependence in the prediction of the two branching ratios, the Mark II measurements[25] can be used to set limits on interactions violating lepton universality. The sensitivity of the τ decays into K^* and ρ to vector type interactions is similar to the sensitivity of the decays into K and π to axial-vector interactions.

4.3 Multiprong Decays

The experimental determination of exclusive branching ratios in multi-hadronic final states requires both π/K separation and good π° detection. The measurements of exclusive channels have therefore large errors and, more important, strong correlations with other decay modes.

An alternative approach is to measure different inclusive decay modes. With the results submitted to this conference there are now enough measurements to determine the branching ratios of all individual τ decays. In this section I describe the new measurements and in Sect. 5 an attempt of global fit of the τ branching ratios to all experimental data is presented.

4.3.1 Topological Branching Ratios

The determination of the charged multiplicity is the basic measurement in the multiprong decays. No τ decays have been positively identified yet with more than three charged particles in the final state. The upper limits on the 5-prong branching ratio are listed in Table 5. They were obtained from samples of data in the 1-5 topology. The particle on the single prong side is often required to be a lepton in order to reduce the background from hadronic events. Also the 3-prong τ decays can contribute to that topology if a photon from a final state π° has converted in the detector. The limits in Table 5 are obtained under the assumption that all events passing the selection contain genuine 5-prong τ decays.

The limit on the 5-prong decays is much lower than the experimental error on the branching ratio into 3 prongs. Therefore the sum of 1-prong and 3-prong decays can be constrained to unity in the experimental analysis. Two different methods were used to determine the branching ratio into 3 prongs. In the first method only the clean 1-3 topology is used. The direct result of such an analysis is the product of the branching ratios into

TABLE 5

Multiprong Branching Ratios

Experiment	Topologies used			$BR(\tau \to 3$ prongs) in %	$BR(\tau \to 5$ prongs) in %	
Mark II[25]	1-1,	1-3,	3-3	14.0 ± 2.0 ± 1.0	< 0.5	(95% C.L.)
CELLO[7]	1-1,	1-3,	3-3	14.7 ± 1.5 ± 1.3	< 0.9	(95% C.L.)
MAC	1-1,	1-3,		13.5 ± 0.3 ± 0.6	< 0.16	(95% C.L.)
[MAC		1-3		13.6]		
DELCO		1-3		12.4 ± 0.6 ± 1.4	< 0.3	(95% C.L.)
TPC[26]		1-3		14.8 ± 0.9 ± 1.7	< 0.3	(90% C.L.)
Average				13.6 ± 0.6		

1 and 3 prongs. Since the sum of the two is constrained to 1, the individual branching fractions can be determined from this result. This is an absolute measurement and therefore one has to know the cross section for τ-pair production, the integrated luminosity of the experiment and the absolute efficiency of the event selection. In the second method the ratio of events in the 1-3 and the 1-1 topology is measured. Sometimes also the 3-3 topology is added to the analysis providing a cross check. The result is independent of the τ-pair cross section and of the integrated luminosity. The understanding of the background is the dominant systematic problem in these analyses.

The MAC group has determined the 3-prong branching ratio with both methods and gets consistent results. The two entries in Table 5 come from the same data sample and the value in brackets is merely used as a cross check. Since the measurements of the 3-prong branching ratio have reached a considerable precision, it is necessary to discuss the treatment of K°_s. They are not reconstructed in the experiments listed in Table 5. Therefore a K°_s decaying into charged pions is counted as 2 prongs in the final state. To get the weighted average of all measurements I have added the statistical and systematic error in quadrature and assumed that the systematic errors of the different experiments are independent.

4.3.2 π° in 3-prong Decays

The τ decays into the resonances $A(1270)$ and $\rho'(1600)$ are expected to be the main contributions to the 3-prong decays. The decay into $A(1270)$ leads to 3 charged pions in the final state while in the ρ' case there is an additional π°. The DELCO group and the MAC group have measured the fraction of 3-prong τ decays with one or more π° in the final state. In both detectors the measurement is based on the 1-3 prong data sample. The π° are identified as signals in the electromagnetic shower counter in excess to the signal of three charged pions. Two problems occur in the analysis: first a charged π can interact with a nucleus in the shower counter and produce electromagnetic energy. On the other hand a π° can miss the shower counter or not pass the selection criteria. It is obvious that the two problems are correlated. If the criteria for the definition of a π° get more stringent, the probability to misidentify the products of a nuclear reaction as a π° becomes smaller but at the same time more real π°'s are missed.

The DELCO shower counter consists of three layers of scintillator with interspaced lead plates. The corrections of the result due to the two problems discussed above are both between 20% and 30%. They are estimated from the observed longitudinal distribution of the signal over the three layers. This distribution is characteristic for the electromagnetic showers caused by photons and quite different if energy is deposited by the interaction of a charged π. The MAC group used the good spatial resolution of the lead plate shower chamber to detect π^0 well separated from the charged tracks. The criteria to define a π^0 are more stringent than in the DELCO analysis. In consequence, nuclear reactions of charged pions lead only to 5% background in the sample of τ decays with a final state π^0. On the other hand, 68% of the events without detected neutral energy contain a π^0. Both groups do not attempt to count the number of π^0 or to identify the charged decay products. The preliminary results are

$$F = \frac{BR(\tau \to XXX + n\pi^0 + \nu)\ ,\ n \geq 1}{BR(\tau \to 3\text{ prongs})} = \begin{cases} 0.55 \pm 0.04 \pm 0.09 & \text{(DELCO)} \\ 0.43 \pm 0.03 \pm 0.06 & \text{(MAC)} \end{cases} \qquad (28)$$

where X is a charged π or kaon. The systematic uncertainties of the two measurements are independent because the relative size of the two corrections is so different. Therefore the weighted average of the two results gives a good estimate of the best value of the fraction F:

$$F = 0.48 \pm 0.06\ . \qquad (29)$$

In order to compare this result with the predictions of the τ decay rates into $A(1270)$ and $\rho'(1600)$ the small contribution from decays with kaons has to be subtracted. The measurement of kaons in multiprong τ decays is discussed in the next section and the comparison with theory is described in Sect. 5.

4.3.3 Kaons in 3-prong Decays

The τ decays into three charged and no neutral hadrons are illustrated in Fig. 2. The decay into three pions, shown in Fig. 2a, is the main contribution to the 3 hadron final state. It is described in the quark model as the Cabibbo favored decay of the virtual W into $u\bar{d}$ followed by the creation of a $u\bar{u}$ and a $d\bar{d}$ pair from the vacuum. The 3π final state is expected to be dominated by the $A(1270)$ resonance. Since the decay is mediated by the axial-vector part of the weak interactions the rate can be estimated with the Weinberg sum

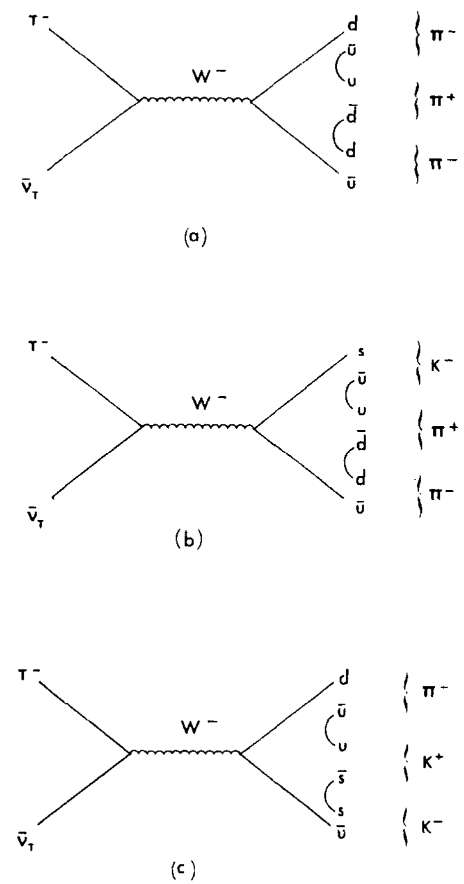

Fig. 2 Schematic diagram for the τ decays into three mesons.

rules given in Sect. 4.1. Such an estimate gives a branching ratio of the τ into three charged pions of about 4%.

The decay into $K\pi\pi$ is mediated by the Cabibbo suppressed part of the weak interactions (Fig. 2b). Its rate is therefore reduced by roughly a factor $tg^2\theta_c \simeq 0.05$ as compared to the 3π decay. In the standard picture the $K\pi\pi$ decay proceeds via the Q resonances (Table 4) and its branching ratio can be estimated with the Das-Mathur-Okubo sum rules. The prediction for the total branching ratio of the τ decay into $K\pi\pi(\pi^\circ)$ is[24]

$$BR(\tau^- \to K^-\pi^+\pi^-(\pi^\circ)\nu) \simeq 0.1\% \tag{30}$$

under the assumption of equal contributions from the $Q(1280)$ and $Q(1400)$ resonances. If one of the resonances dominates the decay this prediction can change by up to 30%.

In Fig. 2c the decay of the τ into $KK\pi$ is illustrated. A pair of strange quarks is created which yields two kaons in the final state. In the standard picture the decay proceeds through the $\rho'(1600)$:

$$\tau \to \rho'(1600)\nu \to K^*K\nu \to KK\pi\nu \ . \tag{31}$$

The dominant decay of the $\rho'(1600)$ leads to four pions, while its K^*K decay has a branching fraction of $9\pm2\%$.[15] In the quark model this is explained with the small probability to create a $s\bar{s}$ pair out of the vacuum. The τ decay into K^*K is also suppressed due to limitations in the available phase space. Since it is mediated by the nonstrange vector part of the weak interactions the rate can be derived with the CVC theorem from the cross section $\sigma(e^+e^- \to K^*K)$ (Sect. 4.1). However, the available data on this cross section are limited and a large isoscalar contribution has to be subtracted. The CVC prediction of the τ branching fractions can therefore only be trusted at the factor-of-two level. The result of the calculation is[24]

$$BR(\tau^- \to K^-K^+\pi^-\nu) \simeq 0.2\% \ . \tag{32}$$

In summary, the two multiprong decays of the τ with inclusive kaons are both strongly suppressed and a good K/π separation is needed in order to measure the branching ratios.

The DELCO collaboration and the PEP4-TPC collaboration have recently studied kaons in multiprong τ decays. The DELCO analysis is an extension of the single prong kaon measurement (Ref. [13], see also Sect. 3.2.2). The kaons are separated from the pions with a large solid angle Čerenkov counter if their momentum is well above the π threshold of the counter. Low momentum particles are not identified. In order to separate the two decays shown in Fig. 2b and 2c the charge Q_K of the identified kaons is compared with the charge Q_τ of the parent τ. In the Cabibbo suppressed decay there is one kaon in the final state with the same charge as its parent τ while the decay Fig. 2c yields a K^+K^- pair. In a selected sample of τ events in the 1-3 topology 9 events are found with identified kaons.[24] The estimated background is 0.9 ± 0.3 events due to misidentified pions and the contamination from hadronic events is estimated to be 0.8 ± 0.4 events. The charge correlation of the 9 observed events is:

1 kaon identified,	$Q_K = Q_\tau$	:	6 events	(33a)
1 kaon identified,	$Q_K = -Q_\tau$	:	2 events	(33b)
2 kaons with opposite charge identified		:	1 event .	(33c)

The 3 events in (33b) and (33c) are due to the $KK\pi$ decay while both decay modes can contribute to the 6 events in (33a). Since it is not possible to separate the two modes completely the resulting branching ratios are correlated. The correlation is shown in Fig. 3 and the most probable values are:[24]

$$\begin{aligned} BR(\tau^- \to K^-K^+\pi^-\nu) &= \left(0.22^{+0.17}_{-0.11}\right)\% \\ BR(\tau^- \to K^-\pi^+\pi^-(\pi^\circ)\nu) &= \left(0.22^{+0.16}_{-0.13}\right)\% \end{aligned} \tag{34}$$

The systematic uncertainties are much smaller than the statistical errors given in (34). Due to the distinct charge configurations (33b) and (33c) the existence of the τ decay into $KK\pi$ is well established and the statistical significance for the decay into $K\pi\pi$ is also larger than 2σ (see Fig. 3). The two measured branching ratios are in agreement with the theoretical predictions.

The PEP4-TPC collaboration has also investigated inclusive kaons in 3-prong τ decays.[26] The kaons are statistically separated from the pions with a fit to the dE/dx distribution in the TPC and not on a track-by-track basis as in the DELCO experiment. In order to enhance the kaon content the TPC analysis is restricted to one selected track per event. The decays shown in Fig. 2b and Fig. 2c both yield a kaon with the same charge as the parent τ and there are two tracks with same charge in each 3-prong decay. From these two tracks the one with higher momentum is analyzed because the kaon is often faster than the lighter pions. The fit to the dE/dx distribution of the selected tracks yields 6.5 ± 3.6 kaons. It is clear that the two decay modes cannot be separated if only same-charge tracks are studied. Therefore the upper limit is obtained on the sum of the two branching ratios[26]

$$BR(\tau^- \to K^- + 2 \text{ charged} + \text{neutrals}) < 0.6\% \quad (90\% \text{ C.L.}) \,. \tag{35}$$

This value is consistent with sum of the the DELCO measurements.

The measurement of inclusive kaons in single prong decays is closely related to the decays discussed in this section. The recent DELCO result[13]

$$BR(\tau \to K\nu + n\pi^\circ) = 1.71 \pm 0.29\% \quad (n \geqslant 0) \tag{36}$$

is in excellent agreement with the predictions of the standard picture which includes the τ decays into K, K^*, the two Q resonances and into K^*K.

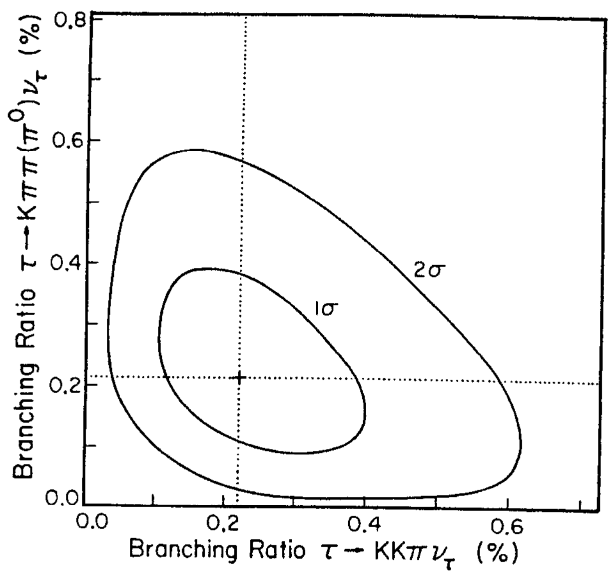

Fig. 3 DELCO:Contour plot of the confidence region for the branching ratios $BR(\tau \to KK\pi\nu)$ and $BR(\tau \to K\pi\pi(\pi^\circ)\nu)$.

In summary all predicted decays with inclusive kaons have been observed. Some of the individual branching ratios still have large uncertainties but the measurements confirm the suppression expected in the standard picture.

5. PHENOMENOLOGICAL FIT OF THE BRANCHING RATIOS

The number of τ decay modes is quite small in the standard picture as outlined in Sect. 4.1. All predicted decays are listed in Table 6. Some of the branching ratios are measured directly but many experiments determine a combination of several decays, e.g. inclusive measurements. Also, at SPEAR and DORIS the $\tau\bar{\tau}$ events are often tagged by the requirement that one of the τ's decays into an electron or a muon. The result of such an analysis is the product of two branching ratios. The branching fractions of individual τ decays have to be determined from an overall fit to the available experimental data.

The results of the fit are used to check whether the individual branching ratios agree with the theoretical prediction. Because the new measurements of inclusive π° and kaons in 3-prong decays allow for the separation of the different multiprong decay modes, the branching ratios of all predicted τ decays can be now determined from the data. The sum of the measured branching ratios provides a new test of the standard picture and can reveal unexpected decays.

5.1 Selection of the Data

The selection of the data used in the analysis is based on the Review of Particle Properties.[15] Of course the preliminary results submitted to this conference are also included as well as measurements published in 1984 which are not yet listed in Ref. [15]. In order to get reasonable results from the fit, the input data should be uncorrelated and they should not rely on assumed branching ratios of τ decays other than the measured ones. For similar reasons I avoid measurements with large systematic errors whenever possible without losing too much information. With these criteria three types of measurements are not included in the fit:

- Results on multiprong decays from SPEAR/DORIS have systematic uncertainties caused by the hadronic background in the data samples. All these measurements are repeated, however, in the much cleaner environment of PEP/PETRA. Therefore the low energy results can be ignored without loss of information.

TABLE 6

Fitted Branching Ratios in %

Decay	Sum-free	Sum-constrained
$\tau \to e\nu\nu$	17.8 ± 0.7	18.9
$\tau \to \mu\nu\nu$	17.3 ± 0.7	18.4
$\tau \to \pi\nu$	10.8 ± 0.4	11.5
$\tau \to \rho\nu$	21.9 ± 1.5	24.0
$\tau \to A(1270)\nu$	12.7 ± 1.8	14.2
$\tau \to \rho'(1600)\nu$		
$\to 4\pi\nu$	8.5 ± 1.2	8.2
$\to 2\pi\nu$	(~1.0)	1.0
$\to K^*K\nu$	0.7 ± 0.5	0.7
$\to \eta\pi\pi\nu$	(~0.5)	0.5
$\tau \to K\nu$	0.7 ± 0.2	0.8
$\tau \to K^*\nu$	1.5 ± 0.4	1.5
$\tau \to Q\nu$	0.3 ± 0.3	0.3

- Some of the experiments published soon after the discovery of the τ determine its branching ratio into electrons from selected events of the type eX, where X is a minimum ionizing particle, i.e. a π or a μ.The resulting τ branching ratio into electron relies on a combination of assumed branching ratios into μ, π and ρ. Since this combination depends strongly on the apparatus and on the event selection I do not include such measurements in the fit.
- The recent CELLO results[7] of different decays with inclusive π° are highly correlated with each other. Due to the low number of observed events also the statistical significance of the results is not very strong. Therefore these measurements are left out, but all other results from Ref. [7] are included in the fit.

These selection criteria lead to the data listed in Table 2 which are used in the fit. There are still some correlations between different entries. For example the three results from the Mark II paper[10] are based on the same data sample and have, therefore, common systematic uncertainties. I did not attempt to take these correlations into account and the different entries are assumed uncorrelated. Systematical and statistical error are added in quadrature for each measurement to determine its weight.

5.2 Description of the Fit

The fit of the branching ratios for the τ decays into resonances requires some assumptions since the experimental data on the final states with one charged and several neutral hadrons are very limited. These single prong decays are related to multiprong decays via Clebsch-Gordon coefficients if the hadronic τ decays proceed through resonances. One has to know, or assume, however, the decay chains of the resonances. The branching ratios of the different three prong decays can be determined from the inclusive measurements of π° and kaons in multiprong decays.

The largest contribution to the unmeasured single prong decay rate comes from the decay $\tau^- \to \pi^-\pi^\circ\pi^\circ\nu$ which is dominated by the $A(1270)$. The main decay chain of this resonance is well established[15] as $A(1270) \to \rho\pi \to \pi\pi\pi$ and the two possible charge combinations have the same branching fraction:

$$\frac{BR(\tau^- \to \pi^-\pi^+\pi^-\nu)}{BR(\tau^- \to \pi^-\pi^\circ\pi^\circ\nu)} = 1 \ . \tag{37}$$

The other decays of the $A(1270)$ have very small branching ratios and may be neglected in the fit.

The τ decays proceeding through the $\rho'(1600)$ cause some problems. The branching ratios of this resonance are measured only with limited accuracy and the decay chains are not established.[15] Therefore I treat the decays to the four possible final states listed in Table 6 as independent decays of the τ. The main decay of the ρ' leads to four pions in the final state and the intermediate states are not well determined. The particle data group concludes[15] from the absence of the neutral decay $\rho' \to \rho^\circ\pi^\circ\pi^\circ$ that the most likely chain is $\rho' \to A(1270)\pi \to \rho\pi\pi \to 4\pi$. Under this assumption the branching ratios of the two possible τ decays are related by:

$$\frac{BR(\tau^- \to \pi^-\pi^+\pi^-\pi^\circ\nu)}{BR(\tau^- \to \pi^-\pi^\circ\pi^\circ\pi^\circ\nu)} = 3 \ . \tag{38}$$

The other τ decays not directly determined from the data have small branching ratios and the fit is not sensitive to the details of the involved resonances. The branching ratio for τ decays into five charged particles is smaller than 0.16% (Table 5). Therefore all modes with five hadrons in the final state are neglected in the fit although a small portion of the K^*K decays leads via two K^*, to a 5π final state.

5.3 Results of the Fit

The results of the fit are summarized in Table 6. Most of the hadronic τ decays are discussed above and here I summarize the conclusion from the comparison of theory and fit. The branching ratio of the decay into ρ confirms the CVC theorem at the 15% level and the decay into K^* is in reasonable agreement with the Das-Mathur-Okubo sum rules. The small branching ratios into Q and K^*K are measured with large uncertainties but are consistent with the also rather imprecise theoretical predictions.

The decay into $A(1270)$ provides a test of the sum rules and gives therefore information on the breaking of the SU(3) symmetry. The Weinberg sum rules given in Sect. 4.1 relate the branching fractions of the τ decays into $A(1270)$ and into ρ. The two sum rules yield two different relations and with the measured branching ratio of the τ decay into ρ from Table 6 one gets:

$$BR(\tau \rightarrow A(1270)\nu) = 6.7\% \text{ and } 8.7\% \quad . \tag{39}$$

The two predictions should be equal and the difference indicates the limitations of the sum rules.

The experimental determination of the branching ratio (39) is based entirely on the final state with 3 charged pions and the relation (37) is assumed. Since the $A(1270)$ decays are well measured the uncertainty of this relation does not influence the measured τ branching ratio significantly. The result of the fit (Table 6) shows that the prediction of the sum rules are correct only within a factor of two. Therefore, either the SU(3) symmetry is still considerably broken at masses around 1.2 GeV/c^2 or the spectral functions are not dominated by the ρ and $A(1270)$ resonances as assumed in Sect. 4.1.

The τ decay rate into 4π are predicted by the CVC theorem from the cross section of e^+e^- annihilation into 4π if the decay proceeds through vector interactions and if there is no isoscalar contribution to the annihilation. Axial-vector and isoscalar interactions leading to four pions violate the conservation of the G-parity. Therefore the requirements of the CVC theorem should be fulfilled to a good approximation. There are two possible final states in both processes and they are related by [20]:

$$\frac{\Gamma(\tau^- \rightarrow \nu_\tau \pi^- 2\pi^\circ)}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e)} = \frac{3}{2\pi\alpha^2 m_\tau^8} \int_0^{m_\tau^2} dQ^2 Q^2 (m_\tau^2 - Q^2)^2 \tag{40a}$$

$$\times (m_\tau^2 + 2Q^2) \left[\tfrac{1}{2}\sigma_{e^+e^- \rightarrow 2\pi^- 2\pi^+}(Q^2) \right]$$

and

$$\frac{\Gamma(\tau^- \rightarrow \nu_\tau 2\pi^- \pi^+ \pi^\circ)}{\Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_\tau)} = \frac{3}{2\pi\alpha^2 m_\tau^8} \int_0^{m_\tau^2} dQ^2 Q^2 (m_\tau^2 - Q^2)^2 \tag{40b}$$

$$\times (m_\tau^2 + 2Q^2) \left[\tfrac{1}{2}\sigma_{e^+e^- \rightarrow 2\pi^- 2\pi^+}(Q^2) + \sigma_{e^+e^- \rightarrow \pi^+\pi^- 2\pi^\circ}(Q^2) \right] \quad .$$

The most recent data on the e^+e^- cross sections in the relevant energy range are compiled by Gilman and Rhie and the result of their integrations is [20]:

$$BR(\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^\circ\nu) = 4.9\% \tag{41a}$$

$$BR(\tau^- \rightarrow \pi^-\pi^\circ\pi^\circ\pi^\circ\nu) = 1.0\% \quad . \tag{41b}$$

There is an error due to the uncertainties in the measurements of the cross sections which is of the order of 30% and 10% for the branching ratio (41a) and (41b), respectively.

In τ decays only the 3-prong mode is well determined from the data. The result of the fit

$$BR(\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^\circ\nu) = 6.4 \pm 0.9\% \tag{42}$$

agrees with the CVC prediction. The one-prong decay is measured by the CELLO collaboration [7]:

$$BR(\tau^- \rightarrow \pi^-\pi^0\pi^0\pi^0\nu) = 3.0 \pm 2.7\% \ . \tag{43}$$

Since the accuracy is very limited and the result is strongly correlated with other decays this measurement is not used in the fit. The branching ratio (43) can be calculated in two different "models." The CVC prediction (41b) is valid independently of the intermediate states through which the τ decay and the annihilation proceed. The relation (38) with the fitted branching ratio of the 3-prong decay yields $2.1 \pm 0.3\%$. The errors do not include systematic uncertainties for the validity of the theoretical assumptions. The CELLO result is not accurate enough to distinguish between the two models and a systematic uncertainty of about 1% remains for the branching ratio of the single prong decay (43). The standard picture with relation (38) is assumed in the fits used for the calculation of the branching ratios given in Table 6.

Since the $\rho'(1600)$ has considerable branching fractions into $\pi\pi$ and $\eta\pi\pi$ [15] these channels should also exist in τ decays. As of yet they are not observed. The $\eta\pi\pi$ state has not been searched for and it could obscure the measurements of single prong decays with π^0 because the η preferentially decays to neutral final states. The CELLO collaboration has estimated the branching ratio of the decay $\tau^- \rightarrow \pi^-\pi^0\nu$ with $(\pi^-\pi^0)$ masses above the $\rho(770)$ [7]:

$$BR(\tau^- \rightarrow \pi^-\pi^0\nu) = 0.3 \pm 0.3\% \quad \text{(non-resonant)} \ . \tag{44}$$

The two τ branching ratios listed in Table 6 are educated guesses based on the poorly measured $\rho'(1600)$ branching fractions[15] and the CELLO estimate (44).

In conclusion most of the predicted τ decays are well determined by the available measurements and the experimental branching ratios for individual decays agree with the predictions of the standard model. Therefore, the sum of all known branching ratios can reveal indirect evidence for exotic τ decays which are not yet observed. The branching ratios listed in the first column of Table 6 sum up to $93.7 \pm 2.7\%$. The error does not include the correlations between different measurements used in the fit nor systematic uncertainties due to the supposed relations between certain decay modes. The least justified assumptions are Eq. (38) for the single prong mode of the decay into 4π and the values given in Table 6 for the decays into $\pi\pi$ and $\eta\pi\pi$. The sum of these three branching ratios is about 3.6% and the uncertainty due to the assumptions is probably of this order. The measured sum of all branching ratios is therefore consistent with 100%. However, with the present data one cannot exclude exotic decays with branching fractions of up to 10%.

If there are no exotic τ decays and if the assumptions of the fit are correct the branching ratios in Table 6 have to add up to 100%. The most probable values for the individual branching ratios are then obtained by repeating the fit with the sum constrained. All assumptions and the weights of the entries listed in Table 2 remain unchanged. The results of this constrained fit are listed in the last column of Table 6. The comparison of the two fits shows the largest difference in the three connected τ decays into e, μ and π and in the decay into ρ. The branching ratios increase by 1.7 and 1.5 standard deviations, respectively. Also the branching ratio of the $A(1270)$ decay is raised but the other decays are not changed significantly. Therefore the constraint on the sum increases the decays with large branching fractions which is obviously the best way to account for the missing 6.3% in the sum.

In summary the results of the fit are compatible with the supposition that there are no exotic τ decays, i.e. that the list given in Table 6 is complete. If one accepts all assumptions of the standard model for hadronic τ decays one can constrain the sum of the predicted branching ratios to 100% to obtain the most probable values for the branching ratios of the individual decays. They are listed in the last column of Table 6.

6. MASS OF THE τ NEUTRINO

The problem of neutrino masses has recently attracted increasing interest. The theory of the weak interactions no longer requires massless neutrinos as a basic input but grand unified theories may lead to massive neutrinos. Experimentally, an indication has been found for a non-zero mass of the electron neutrino[27],[28] although it is not yet confirmed. The topic of neutrino masses is vast and rapidly evolving. I will concentrate here on the experimental investigation of the τ neutrino and refer the reader to recent reviews[29] for other aspects.

An upper limit on the ν_τ mass of 250 MeV/c^2 was obtained at SPEAR from the electron[30] and π[10] momentum spectrum in the decays $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \pi\nu$, respectively. In order to obtain a limit from the electron spectrum one has to assume that the τ decay is mediated by pure V-A interactions. The momentum of the π depends quadratically on the neutrino mass and is, therefore, not very sensitive to small masses. An alternative method is to study the invariant mass distribution in multihadronic τ decays. Its end-point is given by $m_\tau - m_{\nu_\tau}$ and is independent of the interaction responsible for the τ decay. In order to increase the sensitivity to m_{ν_τ}, the decay modes with small Q values should be selected for such an analysis. This method requires large and background free samples of 3-prong τ decays which can be obtained only at the higher PEP/PETRA energies.

The DELCO and the Mark II collaborations have recently improved the upper limit on m_{ν_τ} with a study of the τ decay into $\rho'(1600)$. The central value for the mass of this resonance is only 200 MeV/c^2 below the τ mass and its width is about 300 MeV/c^2. The invariant mass spectrum extends therefore to the end-point where the phase space suppression is sensitive to the neutrino mass. The Mark II group analyses the 4π channel and the DELCO group the $KK\pi$ mode of the K^*K decay.

The K^*K decay used in the DELCO analysis has the lowest Q value of all observed τ decays. The mass region near the endpoint is, therefore, kinematically enhanced. In a first step, the branching ratios of the decays $\tau \rightarrow KK\pi\nu$ and $\tau \rightarrow K\pi\pi(\pi^\circ)\nu$ are measured ([24], see also Sect. 4.3.3) They are both small–of the order of 0.2%–in agreement with the standard model where the 3-prong decays are dominated by the three and four π final states.

In the second step, events with a $KK\pi$ decay are selected and the invariant mass is calculated. This requires the correct mass assignment to all three daughter particles and thus both kaons in the event have to be identified. The identification of two kaons substantially suppresses the background from the dominant τ decay with three charged pions since the probability for misidentification of two particles in the same event is small. Therefore, the criteria for the kaon identification is relaxed as compared to the measurement of the branching ratios. Four events with two identified kaons are found in a data sample with an integrated luminosity of 150 pb^{-1}. The estimated background is less than .06 events both from hadronic events and from π misidentification. The mass resolution function is dominated by the errors of the momentum measurement. It is determined event by event with a Monte Carlo simulation based on the measured resolutions of the apparatus and the three measured momentum vectors of the event (Fig. 4). The maximum likelihood fit of the mass distribution yields an upper bound for m_{ν_τ} of:

$$m_{\nu_\tau} < 157 \text{ MeV/c}^2 \quad \text{at} \quad 95\% \text{ C.L.} \; . \qquad (45)$$

Since the sensitive part of the mass spectrum is near the endpoint and is determined by the available phase space the fit does not depend on theoretical assumptions on the shape of the spectrum. In particular the bound (45) is valid under the standard assumption of the decay chain $\tau \rightarrow \rho'(1600)\nu \rightarrow K^*K\nu \rightarrow KK\pi\nu$ and also for a simple 3-body phase space decay of the $KK\pi$ system.

The Mark II analysis is based on the decay $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^\circ\nu$ which is also thought to proceed through the $\rho'(1600)$. The mass resolution function is assumed to be Gaussian and the width is determined by a Monte Carlo simulation as a function of m_{ν_τ}. The average value of the mass resolution is 53 MeV/c^2. Only events with a 4π mass above 1.5 GeV/c^2 are used in this analysis. As in the DELCO measurement, it was checked that the result is not sensitive to assumptions on the shape of the mass distribution. A first limit of

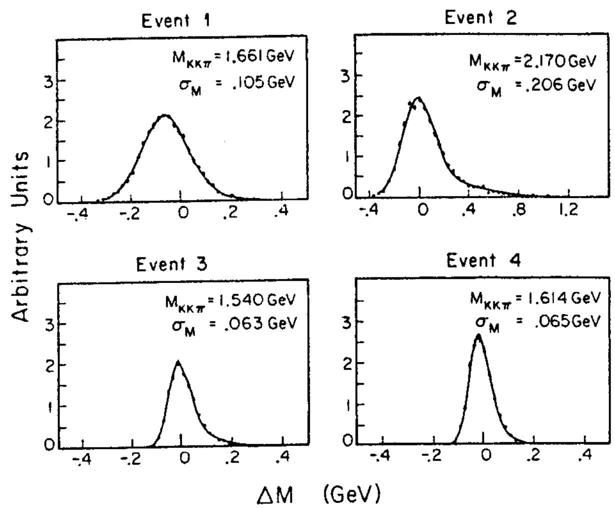

Fig. 4 DELCO: Individual $KK\pi$ mass resolution functions for the four events used to determine an upper bound on m_{ν_τ}; ΔM is the difference in mass with and without resolution.

$m_{\nu_\tau} > 164$ MeV/c^2 has been published in Ref. [31] and an update of the measurement is submitted to this conference. New data are added and the complete data sample has an integrated luminosity of 220 pb^{-1}. The event selection and the fitting procedure have not changed. The number of events used in the analysis increased from 15 to 22 and the mass spectrum of the full data sample is shown in Fig. 5. An upper limit on the neutrino mass of

$$m_{\nu_\tau} < 143 \text{ MeV/c}^2 \quad \text{at} \quad 95\% \text{ C.L.} \qquad -(46)$$

is obtained from the fit to this spectrum.

The DELCO and Mark II results show that the endpoint of the mass spectrum in multihadronic τ decays is very well suited to measure the mass of the τ neutrino. No indications are found for a non-zero mass and the upper limit is substantially reduced. It is model independent and the limitations of both the DELCO and Mark II analyses are the low number of events and the mass resolution.

7. SUMMARY

The knowledge on the τ lepton has considerably increased on account of e^+e^- experiments performed at energies well above production threshold. All results confirm the standard model in which the τ is a sequential lepton. As a consequence, a new trend in τ physics has evolved and becomes apparent in the recent publications. Since it is now generally accepted that the τ is a sequential lepton with its own quantum number and associated neutrino, the aim of the experiments is no longer to study the τ as a particle but to use it as a tool to investigate the weak interactions.

One focus of recent interest is the question whether the coupling constants of the weak and possible superweak interactions are universal. Suppressed τ decays provide very sensitive tests for this universality. From the precise measurements of the Cabibbo suppression in the decay $\tau \rightarrow K\nu$ one can conclude that the difference in the couplings to the τ and to

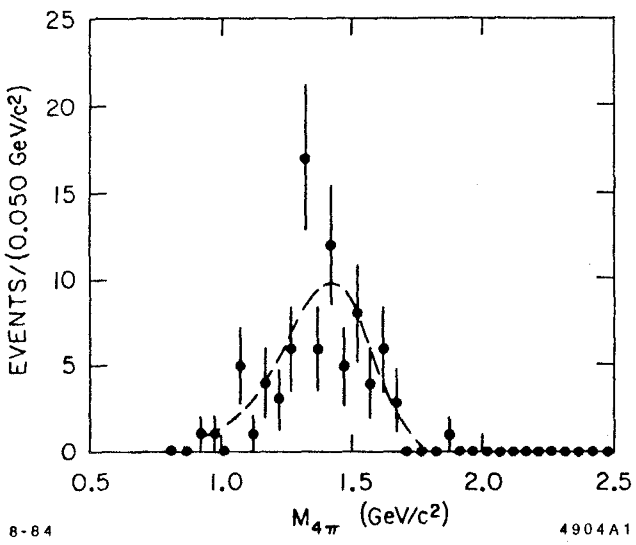

Fig. 5 Mark II: $3\pi^{\pm}\pi^{\circ}$ invariant mass distribution for the selected events.

the μ must be smaller than a few percent of the Fermi coupling. Also all other experimental results support the universality of the couplings. Another basic problem of weak interactions deals with the neutrino masses. Two measurements reported to this conference yield upper limits on the τ neutrino mass which are in the order of the π mass.

A considerable fraction of recent τ experiments test the hadronic weak interactions. For these tests it is important to separate events with hadronic τ decays from $q\bar{q}$ events. This is possible only at high energies and therefore substantial progress was achieved at PEP and PETRA. In the standard model the hadronic τ decays are dominated by resonances and the decay rates into these resonances are predicted from weak interaction theorems like CVC or sum rules. All measured branching ratios are consistent with the weak interaction theory. In particular the CVC theorem is tested at the 15% level in the decay $\tau \rightarrow \rho\nu$. The sum rules are probed in the decays $\tau \rightarrow K^{*}\nu$ and $\tau \rightarrow A(1270)\nu$ and are valid at the factor-of-two level. The sum of all measured branching ratios provides a complementary test of the standard model for τ decays. With the new measurements submitted to this conference it is possible to determine most of the predicted branching ratios from the data and the not yet measured decays are expected to have small branching ratios. The data are consistent with the standard hypothesis that all hadronic τ decays proceed through the resonances listed in Table 6. Some decays of these resonances are poorly known and there is no prediction for the rates of the corresponding τ decays. However, these decays account only for a small fraction of the hadronic τ decays. Since there are gaps in the experimental determination of the branching ratios and in the theoretical predictions one cannot exclude from our present knowledge exotic τ decays with branching ratios of up to 10% which are not included in the standard model.

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References

[1] M. L. Perl, Ann. Rev. Nucl. Part. Sci. 30 (1980), 299.

[2] J. Jaros, Contribution to this Conference.

[3] MAC Collaboration, E. Fernandez et al., Contribution to the 1984 International Conference on High Energy Physics, Leipzig, July 19-25, 1984.

[4] M. Davier, Contribution to this Conference.

[5] Y. S. Tsai, Phys. Rev. D4 (1971), 2821.

[6] TASSO Collaboration, R. Brandelik et al., Phys. Lett. 92B (1980), 199.

[7] CELLO Collaboration, H. J. Behrend et al., Z. Phys. C23 (1984), 103.

[8] PLUTO Collaboration, C. Berger et al., Phys. Lett. 99B (1981), 489.

[9] DELCO (SPEAR) Collaboration, W. Bacino et al., Phys. Rev. Lett. 42, (1979), 6.

[10] MARK II (SPEAR) Collaboration, C. A. Blocker et al., Phys. Lett. 109B (1982), 119.

[11] DASP Collaboration, R. Brandelik et al., Phys. Lett. 73B (1978), 109.

[12] MARK II (SPEAR) Collaboration, C. A. Blocker, Ph.D. Thesis LBL-10801.

[13] DELCO Collaboration, G. B. Mills et al., Phys. Rev. Lett. 52, (1984), 1944.

[14] MARK II Collaboration, C. A. Blocker et al., Phys. Rev. Lett. 48, (1982), 1586.

[15] Review of Particle Properties, Particle Data Group, Rev. Mod. Phys. 56 (1984).

[16] D. A. Bryman et al., Phys. Rev. Lett. 50 (1983), 7.

[17] For a recent example, the calculation of $\tau \rightarrow A\nu$, see J. J. Brehm, Phys. Rev. D 25 (1982), 149.

[18] S. Weinberg, Phys. Rev. Lett. 18 (1967), 507.

[19] T. Das, V. S. Mathur and S. Okubo, Phys. Rev. Lett. 18 (1967) 761.

[20] F. Gilman and S. H. Rhie, SLAC-PUB-3444.

[21] The cross section $e^+e^- \rightarrow \pi^+\pi^-$ was recently remeasured with an overall precision of 4% (OLYA Collaboration, L. Kurdadze, ETPL 37, (1983), 613). This measurement has, as of yet, not been included in predictions of the τ decay rate.

[22] All formulae imply also the charge conjugate decays.

[23] J. M. Dorfan et al., Phys. Rev. Lett. 46 (1981), 215.

[24] DELCO Collaboration, G. B. Mills et al., Caltech preprint CALT-68-1196.

[25] MARK II Collaboration, C. A. Blocker et al., Phys. Rev. Lett. 49, (1982), 1369.

[26] TPC Collaboration, H. Aihara et al., LBL Preprint LBL-108014.

[27] V. Lubimov et al., Contribution to the Conference on High Energy Physics, Brighton, 1983.

[28] Ching Cheng-rui and Ho Tso-hsiu, Phys. Rep. 112, (1984) 1.

[29] See, e.g., P. H. Frampton and P. Vogel, Phys. Rep. 82, (1982) 339 and F. Boehm and P. Vogel, Ann. Rev. Nucl. Part. Sci. 34 (1984).

[30] DELCO (SPEAR) Collaboration, W. Bacino et al., Phys. Rev. Lett. 42, (1979), 749.

[31] MARK II Collaboration, C. Mateuzzi et al., Phys. Rev. Lett. 52, (1984), 1869.