τ BRANCHING RATIOS AND POLARIZATION LIMITS IN e^+e^- INTERACTIONS AT $\sqrt{s} = 34$ GeV

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Received 5 April 1983

Results on the dominant decays of τ leptons produced in e^+e^- interactions at $\sqrt{s} = 34$ GeV are presented. We obtain the branching ratios $BR(\tau \to \rho\nu) = 0.228 \pm 0.033$, $BR(\tau \to \pi\nu) = 0.099 \pm 0.021$, $BR(\tau \to e\nu\nu) = 0.183 \pm 0.031$, $BR(\tau \to \mu\nu\nu) = 0.176 \pm 0.033$. From the laboratory momentum spectra of the observed decay products we determine the τ polarization asymmetry to $(1 \pm 22)\%$ and thereby derive limits for the vector coupling constant v_τ of the τ to the weak neutral current. Tests on universality and factorization are discussed.

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Introduction. Considerable knowledge on the τ lepton has been obtained in low energy e^+e^- interactions both at SPEAR and DORIS [1]. At center of mass energies far above the production threshold as provided by PEP/PETRA, however, the signature of $\tau^+\tau^-$ events with respect to background is much cleaner offering the possibility to extract a virtually background-free sample of τ pairs without restriction to specific decay topologies. The nature of systematic errors, e.g. due to background subtraction, is therefore quite different, as demonstrated by recent measurements of the topological branching fractions [2,3].

Lepton pair production has become increasingly important for tests of electroweak interactions at high energies [4]. Testing universality, measurements of the axialvector coupling constants a_l to the weak neutral current ($l = \mu$ or τ) for both the μ [3,5] and the τ [2,3] have been publiished, based on the angular charge asymmetry. The vector coupling constants v_l can in principle be derived from a measurement of purely weak contributions to the total cross section, the effect, however, is very small at PETRA energies. In order to obtain information on v_l one has to measure parity violating effects either by using longitudinally polarized electron or positron beams, or, since these beams are not available at present, try to measure the polarization of the final state lepton. One excellent candidate for polarization measurements is the τ lepton, the weak decay of which can be used as an analyzer of the polarization. In the standard model [6] the average polarization is expected to be very small, namely 1% at $\sqrt{s} = 34$ GeV assuming $\sin^2\theta = 0.23$. Generally, limits on polarization are an important experimental test of universality and factorization, i.e. single vector boson exchange.

Experiment. The experiment has been performed using the CELLO detector at PETRA. A detailed description of the detector can be found elsewhere [7]. We briefly mention only those detector components relevant for this analysis. The momentum of charged particles is measured in a solenoidal magnetic spectrometer. It covers the polar range $|\cos\theta| < 0.91$. We achieve a momentum resolution of $\Delta p/p = 1.7\%$ p (GeV) using the vertex constraint. Photons and electrons are identified in the barrel liquid argon calorimeter which covers $|\cos\theta| < 0.86$. The energy deposit is sampled in 6 layers up to a maximum depth of 20 radiation lengths (X_0). Each layer consists of channels in 3 orientations. We obtain an energy resolution of $\Delta E/E = 13\%/[E(\mathrm{GeV})]^{1/2}$ and an angular resolution of 4 mrad. Muons are detected in planar proportional chambers surrounding the detector behind 5 to 8 absorption lengths of iron. They cover 92% of 4π. Within the polar range used in the analysis ($|\cos\theta| < 0.85$) the chamber acceptance was 83%. Our trigger logic incorporated a two-charged particle trigger with a momentum cutoff at 250 MeV/c and various calorimetric triggers.

The results presented in this letter are based on 526 $\tau^+\tau^-$ events corresponding to an integrated luminosity of 11.2 [pb^{-1}] at a center of mass energy of 34 GeV. All $\tau^+\tau^-$ decay topologies are recorded by the detector. The selection procedures for the $\tau^+\tau^-$ event sample have been described in a previous publication [2]. We report here on measurements of the decay channels $\tau \to \rho\nu$, $\pi\nu$, $e\nu\nu$, $\mu\nu\nu$. Other channels such as $\tau \to A_1\nu$ and $\tau \to \nu$ + several hadrons are under study. For the analysis of the decays into pion, electron and muon, a subsample of 7 [pb^{-1}] was used. This sample was selected by essentially requiring a minimal total energy of 1.3 GeV in the calorimeter. The efficiencies of the calorimetric triggers were monitored by QED reactions.

Data analysis. In order to study the systematics of our selection procedures and to calculate reliable efficiencies a detailed Monte-Carlo simulation of the detector response to the process $e^+e^- \to \tau^+\tau^-$ was performed. As input we used a standard $\tau^+\tau^-$ four vector generator with initial state radiation of Berends and Kleiss [8]. The produced τ's were allowed to decay according to the measured modes [9] taking into account recent precise measurements of the topological branching ratios [2,3]. We incorporated the known resolutions and efficiencies for the individual detector components relevant to the analysis. In particular, a realistic simulation of electromagnetic and hadronic showers in the liquid argon calorimeter was implemented using standard shower codes [10,11]. The Monte-Carlo events were then subjected to the same reconstruction, selection and analysis programs as the data, including visual scanning to evaluate systematic biases.

$\tau \to \rho\nu$: ρ candidates were selected from one prong decays with one or two additional photons in the same hemisphere. Higher γ multiplicities were not accepted in order to reduce background from A_1 decays and other multi-hadronic decays. Due to the large momenta of the decay particles, the two photons from the π^0 merge into one shower in about 60% of the decays. Thus in addition to the 1 charged + 2 photon final state also the 1 charged + 1 photon topology was considered. No restriction as to the shower development in the liquid argon counter associated with the charged particle was imposed. The photon candidates, however, were subjected to the following criteria:

– A minimal opening angle of 6° between the charged particle and any photon is required to reduce background due to shower fluctuations from hadronic interactions of the charged particle in the calorimeter.

– An energy fraction between 10% and 95% in the first 2 layers corresponding to 3–5 X_0 and energy deposition in a minimum of 2 adjacent layers out of the first 4 layers is required to reduce electronic noise and wide-angle nuclear scatters from the charged particle deep inside the calorimeter.

No photon energy cut was imposed. The above cuts, however, lead to a minimal detectable photon energy of about 150 MeV. Whenever two photons were accepted (about 40% the $\rho \to \pi\pi^0$ decays) a kinematical fit to the π^0 mass was performed in order to improve the ρ mass resolution. A cut of $X^2 \leqslant 10$ was imposed for this one-constraint fit. The spectrum of the effective $\gamma\gamma$ mass prior to the fit is shown in fig. 1a together with the prediction from our Monte-Carlo calculation. The effective mass for the charged particle (assuming a π mass) and the photon (or the 2 photons after the kinematic fit) is shown in fig. 1b. A clear ρ signal is observed. Within the mass range from 0.35 to 1.2 GeV we observe 101 ρ's. The following background contributions have been considered (see fig. 1b):

– τ decaying to $(\pi\pi^0)\nu + \geqslant 1\ \pi^0$ which are not detected, e.g. from $\tau \to A_1\nu$. Attributing a branching ratio of (5 ± 3)% to the channel $\tau \to A_1\nu$, $A_1 \to$ charged $\rho + \pi^0$ [12] [‡1] and (9 ± 4)% to multihadronic nonresonant decays [12] with only one charged particle leads to a background of (15 ± 8) events.

[‡1] The hadronic continuum contribution is chosen to saturate the measured topological branching ratio of the τ into 1 charged particle. The errors try to estimate the systematic uncertainty of this choice.

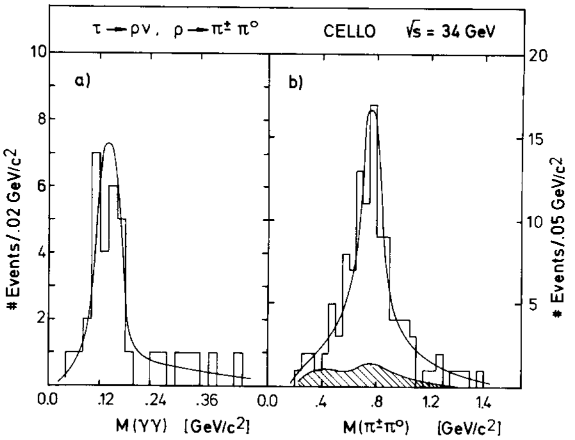

Fig. 1. (a) Distributrion of the invariant two-photon mass for ρ candidates where 2 showers were reconstructed (histogram) and the MC prediction (curve). (b) $(\pi\pi^0)$ invariant mass spectrum (histogram), the MC prediction is superposed (curve). Also shown is the background contribution (Shaded area).

– $\tau \to K^*\nu$. Since we do not distinguish experimentally K's from π's, $K^*(890)$ decays also feed into our ρ sample. Assuming a branching ratio relative to the ρ given by Cabibbo suppression (which is well supported experimentally [13]) yields (2 ± 1) events.

Background due to other processes, such as electrons, muons, or pions together with a radiative photon yielding an invariant mass within the ρ band, is found to be negligible. The average efficiency to detect a ρ from $\tau \to \rho\nu$ in our $\tau^+\tau^-$ sample is 0.45 ± 0.04.

$\tau \to \mu\nu\nu$: Muons were identified in the calorimeter as minimum ionizing particles and by their ability to penetrate the iron filter. A minimal particle momentum of 2 GeV/c and an associated hit in the muon chambers were required. The pion punch through has been determined by Monte-Carlo simulation. In our sample of 47 μ candidates we expect a background of 2 ± 1 pions, where the error is dominated by the uncertainties of the MC calculations. The muon identification efficiency, as obtained by the measured muon chamber efficiencies and MC acceptance calculations, is 0.70 ± 0.06.

$\tau \to e\nu\nu, \pi\nu$: Electrons and pions were separated with the help of their characteristic shower pattern in the calorimeter. Both energy–momentum matching and shower development in depth were employed.

The particles were required to enter the fiducial volume of a calorimeter module. For electrons we asked for a minimum momentum of 1 GeV/c and a shower associated with the track. The energy deposited in the first 3 layers (corresponding to $3X_0$, $2X_0$, and $6X_0$, respectively) had to be greater than 50% of the measured particle momentum. Moreover, the energy fraction deposited in the first two layers had to be greater than 20%. Pion candidates on the other hand were required to have an associated shower consistent with a minimum ionizing particle or an energy deposition in the first 3 layer of less than 50% of the measured particle momentum. About 50% of the pions undergo a hadronic interaction in the calorimeter. From the MC simulation we expect 0.5 ± 0.5 pions in our sample of 60 electron candidates and vice versa 0.7 ± 0.7 electrons in our pion sample. The electron identification efficiency is 0.73 ± 0.04. For pions we furthermore required the extrapolated track to cross a muon chamber, and no muon chamber hit had to be associated with the track. We expect 1.4 ± 1.4 muons in our sample of 34 pion candidates.

A considerable background from $\tau \to \rho\nu \to \pi\pi^0\nu$, due to undetected photons from π^0 decay, is expected. In order to reject ρ's in our pion sample we consider the showers within a cone of 45° half opening angle around the charged particle: We allow up to two additional showers if the invariant mass between the showers and the charged particle is less than 200 MeV/c^2. Thus we include also pions with additional fake photons originating from broad hadronic showers inside the calorimeter. The pion efficiency and the remaining ρ background have been determined by Monte-Carlo techniques. We expect a background from ρ's of 5.4 ± 1.2 events. The error incorporates both an estimate of the systematic errors in the MC simulation and the error in the measured $\tau \to \rho\nu$ branching fraction. Furthermore, the contamination from the Cabibbo suppressed decay $\tau \to K\nu$ in the pion sample has to be subtracted. Using the measured branching fraction BR ($\tau \to K\nu$) = 0.013 ± 0.005 [14] we expect a background of 3.6 ± 1.4 events. The total pion identification probability after all the cuts for muon, rho, and electron rejection is 0.48 ± 0.04.

Results. Branching ratios: The observed event numbers for the four decay channels investigated were corrected individually (as described above). Branching ratios have been obtaining by normalizing to the corrected total number of τ events, i.e. to the measured total cross section for $e^+e^- \to \tau^+\tau^-$ at $\sqrt{s}$ = 34 GeV. We obtain the following values:

$$\mathrm{BR}(\tau \to \rho\nu) = 0.228 \pm 0.025 \pm 0.021\ ,$$

$$\mathrm{BR}(\tau \to \pi\nu) = 0.099 \pm 0.017 \pm 0.013\ ,$$

$$\mathrm{BR}(\tau \to e\nu\nu) = 0.183 \pm 0.024 \pm 0.019\ ,$$

$$\mathrm{BR}(\tau \to \mu\nu\nu) = 0.176 \pm 0.026 \pm 0.021\ ,$$

where the first error is statistical and the second one is systematic. Table 1 summarizes the four τ decay samples, selection efficiencies, and background contaminations with their systematic errors as discussed in the previous section.

Our results for $\tau \to \pi\nu$, $e\nu\nu$, $\mu\nu\nu$ are in good agreement with determinations at lower energies [1,9]. The branching ratio for $\tau \to \rho\nu$ has somewhat improved in the overall error as compared to previous publications [15] based on larger $\tau^+\tau^-$ samples. We attribute this fact to our large selection efficiency for ρ's and to the low background in the $\tau^+\tau^-$ sample (see table 1).

Polarization: In the case of polarized τ's the angular

Table 1
Summary of the four decay samples and their respective efficiencies and background contributions.

Sample	Number of events	Efficiency	Contamination from					
			μ	e	π	ρ	$\pi\pi^0\pi^0$	K, K*
ρ	101	0.45 ± 0.04	0	0	0	–	15.4 ± 8.4	2.3 ± 1.1
π	34	0.48 ± 0.04	1.4 ± 1.4	0.5 ± 0.5	–	5.4 ± 1.2	0	3.6 ± 1.4
e	60	0.73 ± 0.04	0	–	0.7 ± 0.7	0	0	0
μ	47	0.70 ± 0.06	–	0	2.0 ± 1.0	0	0	0

decay asymmetry in the τ rest frame [16] leads to a characteristic distortion of the laboratory momentum spectra of the decay particles. The spectra of ρ, π, e and μ were determined by repeating the above described background subtraction and efficiency correction bin by bin in the respective raw momentum distributions. Fig. 2 shows the raw spectra for the four channels as well as the background contributions. In fig. 3 the corrected laboratory momentum spectra are displayed. For the two-body decays $\tau \to \rho\nu$, $\pi\nu$, an unpolarized τ will produce flat laboratory momentum spectra, whereas a non-zero polarization results in a non-zero slope (see figs. 3a, b). For the leptonic decays $\tau \to e\nu\nu$, $\mu\nu\nu$ the effect is less pronounced but still useful in deriving polarization limits (see figs. 3c, d).

Assuming a standard V – A charged current decay for the τ, the laboratory momentum spectra for the two-body decays as modified by a possible τ polarization are parametrized as [17]

$$df/dx = 1 + 2\alpha P(x - \tfrac{1}{2}), \qquad (1)$$

where x is the fraction of laboratory momentum p available for the decay particle, defined as $x = (p - p_{min})/(p_{max} - p_{min})$. P is the polarization of the τ^- and α a measure of the analysis power of the two-body decay, related to the spin properties of the decay hadron [18], $\alpha = 1$ for π and $\alpha = (m_\tau^2 - 2m_\rho^2)/(m_\tau^2 + 2m_\rho^2) = 0.46$ for the ρ. The spectra for e and μ have the form [17]

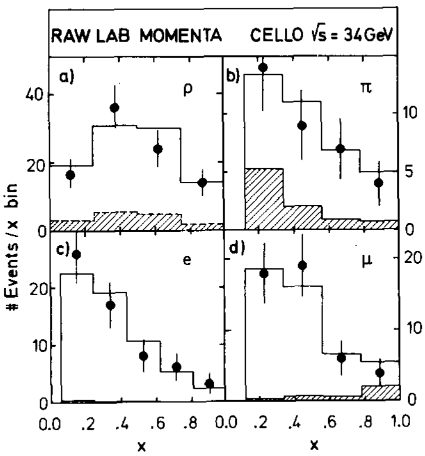

Fig. 2. Raw laboratory momentum distribution (histograms) for ρ, π, e, and μ and respective background contributions (shaded histograms).

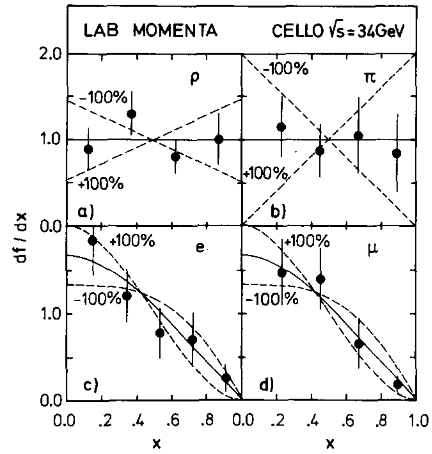

Fig. 3. Corrected laboratory momentum spectra for ρ, π, e, and μ, integrated over the scattering angle. The errors shown include both the statistical (dominant) and the systematic uncertainty. Also shown is the expectation for no polarization (full lines) and for ±100% polarization (dashed lines), for a given scattering angle. Note that the limits for the τ polarization have been determined from the corresponding spectra, separated into forward and backward hemispheres.

$$df/dx = a(x) + P\, b(x), \qquad (2)$$

with

$$a(x) = \tfrac{1}{3}(5 - 9x^2 + 4x^3),$$

$$b(x) = \tfrac{1}{3}(1 - 9x^2 + 8x^3),$$

In the standard V, A ansatz for the weak neutral current [19] the final state polarization for the τ^- is a function of the laboratory scattering angle:

$$P(\theta) = -g(s)[v_e a_\tau + v_\tau a_e 2\cos\theta/(1 + \cos^2\theta)], \qquad (3)$$

with $g(s) = (G_F/\sqrt{2}4\pi\alpha)[sM_Z^2/(s - M_Z^2)]$. G_F is the Fermi coupling constant, α the fine structure constant, s the square of the center of mass energy and M_Z the mass of the weak neutral boson assumed to be 89 GeV/c^2. The first term, independent of $\cos\theta$, contains the product of v_e and a_τ which are known from νe scattering [20], Bhabha scattering [4], and the $\tau^+\tau^-$ charge asymmetry [2]. The term proportional to $\cos\theta$ contains a_e, measured by νe scattering in combination with the Bhabha results, and the unknown quantity v_τ. For the subsequent analysis of electroweak contributions, the laboratory momentum spectra have been determined in the forward (FW) and backward (BW) hemisphere separately, leading to a measurement of the average polarization in each hemisphere.

A fit combining the eight laboratory momentum spectra (FW and BW) derived for the four decay channels yields a polarization asymmetry defined as $A(P) = (\langle P_{FW}\rangle - \langle P_{BW}\rangle)/2$ of

$$A(P) = (+1 \pm 22)\% ,$$

corresponding to the 95% CL limit of $A(P) < 44\%$. According to eq. (3) this result translates into a vector coupling constant of the τ to the neutral weak current of $v_\tau = -0.1 \pm 2.8$. The error is dominated by statistics [‡2]. Comparing to the value for $v_e = -0.04 \pm 0.06$ [20], our result is certainly consistent with the assumption of universality of the weak leptonic couplings. Due to the large error on v_τ, however, no stronger conclusions can be drawn. Still, our measurement constitutes the first attempt to determine v_τ.

Assuming universality ($v_e = v_\tau = v$, $a_e = a_\tau = a$), one can try to test a general property of the weak langrangian [18] which supposedly factorizes into two currents coupled to a single neutral weak boson. With the universality condition, $P(\theta)$ assumes the form

$$P(\theta) = -g(s) 4h_{VA}(1 + \cos\theta)^2/(1 + \cos^2\theta) . \quad (4)$$

Factorization (single Z^0) then implies $4h_{VA} = v \cdot a$. Fits incorporating the universality constraint yield $4h_{VA} = +1.0 \pm 1.4$, which can be compared to the 95% CL limit $v \cdot a < 0.14$ from νe and e^+e^- data [4].

Conclusion. We have determined the branching ratios of $\tau \to \rho\nu$, $\pi\nu$, $e\nu\nu$ and $\mu\nu\nu$ in an e^+e^- experiment at $\sqrt{s} = 34$ GeV where all $\tau^+\tau^-$ topologies were observed with little background. We have measured the laboratory momentum spectra of the four charged decay particles and used them as an analyzer of a possible τ polarization. The measured polarization is compatible with zero and yields for the first time a measurement of the weak neutral vector coupling constant $v_\tau = -0.1 \pm 2.8$. The axial vector coupling of the τ has been determined in a previous publication and supports lepton universality. Comparing the new measurement of v_τ with a recent value on $v_\mu = -0.24 \pm 0.32$ from $\mu^\pm C$ scattering [21] and with $v_e = -0.04 \pm 0.06$ [20], universality seems to hold true also for the vecor couplings of the charged leptons. All coupling measured are in agreement with the predictions of the standard model. Assuming universality, our data is consistent with factorization of the weak neutral current, a necessary ingredient of all single pole models.

[‡2] It should be noted here that the 1σ limit for v_τ derived from $e^+e^- \to \tau^+\tau^-$ total cross section measurements [2] is as large as ±6.5, mainly due to the systematic errors (~8%) involved.

We are indebted to the PETRA machine group and the DESY computer center for their excellent support during the experiments. We acknowledge the invaluable effort of all engineers and technicians of the collaborating institutions in the construction and maintenance of the apparatus, in particular the operation of the magnet system by G. Mayaux and Dr. Horlitz and their groups. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them. This work was partly supported by the Bundesministerium für Forschung und Technologie.

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