OBSERVATION OF THE DECAY $\tau \to \pi\nu$

PLUTO Collaboration

G. ALEXANDER [1], L. CRIEGEE, H.C. DEHNE, K. DERIKUM, R. DEVENISH, G. FLÜGGE, G. FRANKE, Ch. GERKE, E. HACKMACK, P. HARMS, G. HORLITZ, Th. KAHL [2], G. KNIES, E. LEHMANN, R. SCHMITZ, U. TIMM, P. WALOSCHEK, G.G. WINTER, S. WOLFF and W. ZIMMERMANN
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

W. WAGNER
I. Physikalisches Institut der RWTH Aachen, Germany

V. BLOBEL, L. BOESTEN, A.F. GARFINKEL [3], B. KOPPITZ, E. LOHRMANN [4], W. LÜHRSEN and H. SPITZER
II. Institut für Experimentalphysik der Universität Hamburg, Germany

A. BÄCKER, J. BÜRGER, C. GRUPEN and G. ZECH
Gesamthochschule Siegen, Germany

and

H. MEYER, M. RÖSSLER and K. WACKER
Gesamthochschule Wuppertal, Germany

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The decay of the heavy lepton τ into $\pi\nu$ has been established using the magnetic detector PLUTO. The branching ratio is determined to be $\mathrm{BR}(\tau \to \pi\nu) = (9.0 \pm 2.9)\%$ with an additional systematic uncertainty of 2.5%. This value is in good agreement with the theoretical prediction.

The existence of the heavy lepton τ as well as many of its properties have been established by several experiments [1–6].

The simplest interpretation, consistent with published data, is that the τ is a heavy sequential lepton, having its own spin 1/2 massless neutrino. If the τ couples to the conventional weak current one can calculate the partial widths for the leptonic decays [7]:

$$\tau^- \to \nu_\tau e^- \bar{\nu}_e, \quad \tau^- \to \nu_\tau \mu^- \bar{\nu}. \tag{1a, b}$$

Using the pion decay constant $f_\pi = 0.129\ \mathrm{GeV}/c^2$ the ratio of the width of the decay

$$\tau^- \to \nu_\tau \pi^-, \tag{2}$$

to that of decay (1a) can unambiguously be predicted to be [7]

$$\frac{\Gamma(\tau \to \pi\nu)}{\Gamma(\tau \to e\nu\nu)} = \frac{12\pi^2 f_\pi^2}{M_\tau^2} \cos^2\theta_c = 0.57, \tag{3}$$

where θ_c is the Cabibbo angle ($\cos^2\theta_c = 0.95$) and M_τ is the τ mass ($M_\tau = 1.8\ \mathrm{GeV}/c^2$) [4,5].

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[1] On leave from Tel-Aviv University, Tel-Aviv, Israel.
[2] Now at Max-Planck-Institut für Physik und Astrophysik, München.
[3] On leave from Purdue University, Lafayette, IN 47907, USA.
[4] Now at CERN, Geneva, Switzerland.

Other hadronic decay rates can be evaluated by introducing further detailed theoretical assumptions. Most of these decays have been observed with rates in good agreement with these calculations. In contrast, for the pionic decay no compelling experimental evidence has been presented so far [8]. We report here the observation of the pionic decay of the τ. The measured branching ratio is consistent with the theoretical prediction.

The measurement was made at the DORIS electron–positron ring at DESY using the PLUTO solenoidal magnetic detector, which has been described previously [2,9]. The inner volume of the superconducting coil (central field of 2 T) is filled with 14 cylindrical proportional chambers. Two concentric lead cylinders of 0.44 and 1.70 radiation lengths are sandwiched between the proportional chambers at radii of 38 and 59 cm, respectively, for electron identification and photon conversion. The outer cylinder with two subsequent proportional chambers which subtend 55% of 4π is used for electron identification. Muons are distinguished from electrons and hadrons by their ability to traverse the coil and the iron yoke. Muon and electron identification overlap in a solid angle of 35% of 4π.

Heavy leptons observed in this experiment were produced in the reaction

$$e^+e^- \to \tau^+\tau^-, \tag{4}$$

over the center of mass energy range from threshold to 5 GeV. Signal events are those in which one of the heavy leptons decays via channel (2) and the second one by any of the reactions (1a), (1b) or (2). The signature of these events in the detector is two charged tracks, large missing energy and no converted photons. In addition, one of the tracks has to be identified as a hadron, i.e. not being a muon nor an electron.

Photons were recognized if they converted in the detector and left either tracks not pointing to the vertex or a shower not correlated to one of the vertex tracks, or at least two neighbouring clusters of wires set in the proportional chambers. By detecting at least one of the decay photons this yields an efficiency of (78 ± 5)% for π^0 recognition for momenta above 100 MeV/c.

Electrons were identified if they set more than 11 wires in the proportional chambers behind the second lead cylinder. The detection efficiency of this method was determined to be (85 ± 5)% for momenta larger than 600 MeV/c [2].

To separate muons from hadrons we select tracks which point at a muon chamber and have at least 100 MeV/c momentum more than required to penetrate the iron yoke, which gives an effective lower limit to muon momenta observable in the detector of about 1 GeV/c. For each track the mean extrapolation error projected into the muon chamber (σ) has been determined from multiple scattering and from the momentum error. The track is identified as a muon if the nearest detected hit in the muon chamber lies within 5σ from the extrapolated track. Otherwise it is classified as a hadron, except if it extrapolates within 3σ from the chamber edge.

Candidate events were selected according to the following criteria:

(i) two and only two charged tracks of opposite signs are detected,

(ii) at least one charged track fulfills the muon or hadron criteria and points at the lead converter; the track is thus identified as either muon or hadron or electron,

(iii) the difference between the azimuthal angles of both tracks must be $10^\circ < \Delta\phi < 170^\circ$,

(iv) the missing mass squared is greater than $1.4 \times (E_{\mathrm{beam}}/1.8)^2$.

Cut (iv) strongly suppresses $e^+e^-\gamma$, $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\gamma$ final states and favours events with multiple neutrinos. Criteria (iii) and (iv) have already been used in previous analyses [2] to suppress QED events.

From this candidate sample the π decay sample (a) is required to have the signal topology

$$e^+e^- \to \text{hadron track + charged track + no photon.} \tag{5a}$$

For purposes of background evaluation we also select from the above candidate events three control samples. The sample (b) with the topology

$$e^+e^- \to \text{electron track + charged track + no photons,} \tag{5b}$$

and the sample (c) with the topology

$$e^+e^- \to \text{muon track + charged track + no photons,} \tag{5c}$$

are used to determine the background from misidentified electrons and muons respectively.

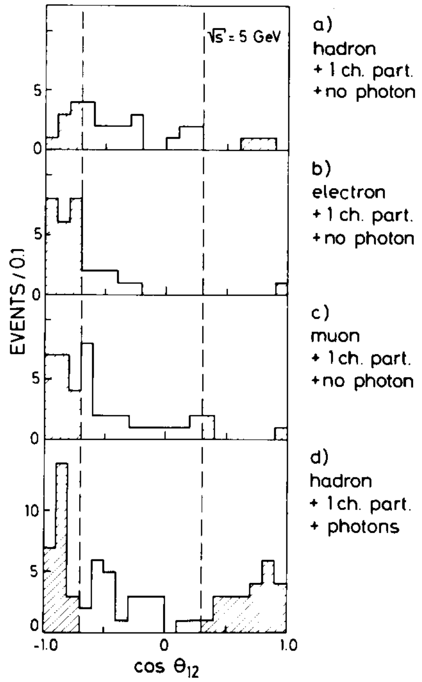

Fig. 1. Cosine of the relative angle θ_{12} between the two tracks for the signature events (a) and different control samples (b), (c) and (d) at 5 GeV center of mass energy. The missing mass cut is not yet applied. The rejected intervals are shaded.

A further sample (d) with topology

$$e^+e^- \to \text{hadron track} + \text{charged track} + \text{photons}, \quad (5d)$$

allows an estimate of events with photons feeding down into the signal channel (a).

Fig. 1 shows the distribution of the cosine of the angle θ_{12} between the two charged tracks for all samples (a) to (d). From fig. 1b one can see that electron–pion confusion is most dangerous in the range of $-1.0 \leqslant \cos\theta_{12} \leqslant -0.7$ which is dominated by Bhabha scattering. Figs. 1c and 1d show peaks in the same region. Consequently all events in this interval are excluded from the analysis. An enhancement in the interval $0.3 \leqslant \cos\theta_{12} \leqslant 1.0$ of sample (d) is found to be largely associated with the $\rho\gamma$ final state. This interval is also excluded. Losses due to these cuts and due to the limited detector acceptance are corrected for by Monte-Carlo studies.

In table 1 the number of events found in five energy intervals between 3.6 and 5 GeV is given for reactions (a) to (d) together with the integrated luminosity.

Table 1
Observed number of events for the topologies (5a) to (5d) after all cuts, evaluation of the background and branching ratios for different energy intervals.

Mean c.m. energy (GeV)	3.6	4.07	4.35	4.6	5.0	4.0 to 5.0
Event samples						
(a) $e^+e^- \to$ hadron + 1 track + no photon	0	5	7	7	13	32
(b) $e^+e^- \to$ electron + 1 track + no photon	1	2	7	2	5	16
(c) $e^+e^- \to$ muon + 1 track + no photon	0	10	15	12	16	53
(d) $e^+e^- \to$ hadron + 1 track + photons	12	27	36	24	23	110
Integrated luminosity (nb^{-1})	610	1560	1230	930	1380	5100
Background events						
Misidentified electrons in (a)	0.2 ± 0.2	0.3 ± 0.2	1.1 ± 0.4	0.3 ± 0.2	0.8 ± 0.4	2.5 ± 0.6
Misidentified muons in (a)	0	0.1 ± 0.05	0.2 ± 0.05	0.1 ± 0.05	0.2 ± 0.05	0.6 ± 0.1
Hadronic background in (a)	0.5 ± 0.2	0.9 ± 0.2	1.2 ± 0.2	0.8 ± 0.2	0.6 ± 0.2	3.5 ± 0.4
$\tau \to \rho\nu$ decay in (a)	0	0.3 ± 0.2	0.5 ± 0.3	0.5 ± 0.3	1.0 ± 0.5	2.3 ± 0.7
Total background in (a)	0.7 ± 0.3	1.6 ± 0.4	3.0 ± 0.5	1.7 ± 0.4	2.6 ± 0.7	8.9 ± 1.0
Signal events		3.4 ± 2.8	4.0 ± 2.8	5.3 ± 2.7	10.4 ± 3.7	23.1 ± 5.8
$BR(\tau \to \pi\nu) \cdot BR(\tau \to \nu + \text{one-prong})$		0.033 ± 0.022	0.031 ± 0.022	0.053 ± 0.027	0.063 ± 0.023	0.043 ± 0.012

Four sources of background to be considered are summarized in the same table:

The number of events due to misidentified electrons can be calculated from the control sample (b) using the electron identification efficiency.

The probability of misinterpreting a muon as a hadron is 2% due to the inefficiency of the muon chambers. The corresponding background is calculated from sample (c).

The sample (d) is used to estimate contributions from hadronic final states, where the photons or π^0's are lost in the detector. The sample also includes contributions from τ decays, which will be considered separately below. They have been determined from Monte Carlo calculations and subtracted. The rest are hadronic events with at least two additional neutral particles, since events with only one neutral particle were removed by the missing mass cut. We assume that these hadronic events contain two, rather than three or more π^0. This is a conservative assumption since it maximizes the estimated background level. Furthermore we assume that the π^0's are isotropically distributed. The contribution from events with two missing charged particles was checked with a control sample of 4-prong events and found to be negligible (less than 0.2 events).

Another source of background comes from τ decays into ρ or A_1, where the charged π from the ρ or A_1 decay is observed, but the π^0's are not. The quoted values are from a Monte-Carlo study of these decays. The A_1 contribution is very small.

The Cabibbo suppressed decay $\tau \to K\nu$ is assumed to be negligible [7]. Evidence for such suppression has been given by the DASP collaboration [10].

Adding up all background sources in the energy range from 4 to 5 GeV, we expect (8.9 ± 1.0) events if the π-decay mode is not present. In contrast we see 32 events, equivalent to an excess of 7 standard deviations. Furthermore in the center of mass region around 3.6 GeV, which is just below threshold for our hadron momentum cut, no events of the signal sample (a) are observed, in agreement with the estimated background rate of (0.7 ± 0.3) events. We therefore conclude that the existence of the decay $\tau \to \pi\nu$ is established.

Fig. 2 shows the momentum spectra for pions (2-body decay) and muons (3-body decay) in the 5 GeV center of mass energy range. The distributions are in good agreement with the theoretical expectation (solid curves). At lower energies the pion and muon spectra get rather similar, again in good agreement with Monte-Carlo calculations.

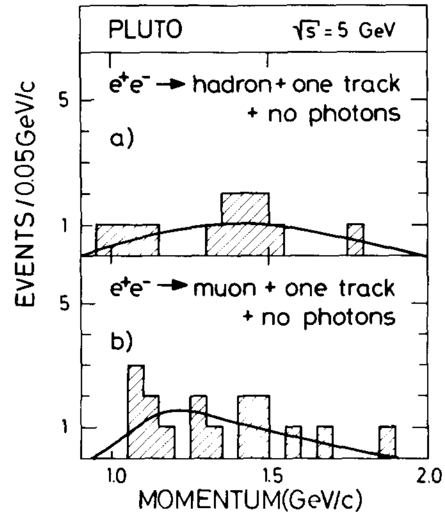

Fig. 2. Momentum distribution of hadrons from reaction (5a) and muons (5c) at 5 GeV center of mass energy. The curves representing the theoretical predictions for V – A coupling and a massless neutrino are normalized to the number of observed events.

To evaluate the branching ratio, we calculate the detection efficiency for events of type (a). Including all cuts the efficiency varies between 0.95% at 4 GeV and 1.95% at 5 GeV center of mass energy, assuming conventional V – A weak interaction and massless neutrinos. We thus obtain the products of the branching ratios into pions $\mathrm{BR}(\tau \to \pi\nu)$ and into one-prongs with no detected photons $\mathrm{BR}(\tau \to \nu + \text{one-prong})$ as indicated in table 1. They agree with each other within errors and yield an average value of

$$\mathrm{BR}(\tau \to \pi\nu) \cdot \mathrm{BR}(\tau \to \nu + \text{one-prong}) = 0.043 \pm 0.012. \tag{6}$$

In our further calculation we use the world average of the leptonic branching ratio of [‡1]

$$\mathrm{BR}(\tau \to e\nu\nu) = (16.7 \pm 1.0)\%. \tag{7}$$

$\mathrm{BR}(\tau \to \nu + \text{one-prong})$ can then be determined to be

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[‡1] This value was calculated from data summarised in ref. [3] and more recent values given in ref. [4].

twice the value of eq. (7) plus hadronic contributions. From the theoretical ρ to electron ratio [7] and our Monte-Carlo we estimate the ρ portion to be 33% of eq. (7). Other hadronic decays constitute a very low fraction [11] (about 1% of eq. (7)). Using these values we get

$$\mathrm{BR}(\tau \to \nu + \text{one-prong}) - \mathrm{BR}(\tau \to \pi\nu) = (39 \pm 2.3)\%,$$

and calculate from eq. (6)

$$\mathrm{BR}(\tau \to \pi\nu) = (9.0 \pm 2.9)\%, \tag{8}$$

and from eqs. (7) and (8)

$$\Gamma(\tau \to \pi\nu)/\Gamma(\tau \to e\nu\nu) = 0.54 \pm 0.17,$$

in good agreement with the theoretical value (3) of 0.57.

All errors are statistical only. Comparing the very clean sample (c) with the results of our Monte-Carlo calculations, we estimate that the systematic uncertainty is of the same order as the statistical error, namely 2.5% in BR($\tau \to \pi\nu$).

To conclude, we have measured the decay of the heavy lepton $\tau \to \pi\nu$ with a branching ratio in good agreement with that expected from the conventional form of the weak interaction [7]. In particular our measurement provides further evidence [6] that the axial-vector part of the weak hadronic current is present in τ decays.

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