EVIDENCE FOR THE $\tau \to \nu\rho\pi$ DECAY MODE

PLUTO Collaboration

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Annihilation of e^+e^- into final states with a single electron has been studied with the PLUTO detector at the DORIS storage ring at CMS energies from 3.6 to 5 GeV. In the sample of 4-prong events without any detected photon we observe 21 events which we assign to the reaction $e^+e^- \to \tau^+\tau^- \to \nu\nu e + \nu\rho^0\pi$. We obtain a branching ratio for $\tau^+ \to \nu\rho^0\pi^+$ of 0.050 ± 0.015 with an overall systematic uncertainty of 30%. The data are consistent with the $\rho\pi$ coming from an A_1 meson.

Studies of the decay modes of the recently discovered [1] heavy lepton τ provide essential information as to its nature and weak interaction properties [2]. It is known experimentally [3] that 70% of all τ-decay modes appear in the one charged particle configuration (one prong). The sum of the branching ratios for the one prong leptonic decays $\tau \to \nu\nu e$ and $\tau \to \nu\nu\mu$ were measured by the SLAC-LBL [4] and PLUTO [3] collaborations to be in the range from 30 to 45%. Preliminary results for the one prong semi-hadronic decay $\tau \to \nu\rho$ have been reported by the DASP collaboration [5]. The three and higher prong topologies, which amount to approximately 30% of all decays, are expected [2] to be due in part to $\tau \to \nu A_1$. It has even been suggested [6] that the $\tau \to \nu A_1$ decay may be the best way of establishing the existence of the A_1 [7,8]. First evidence for the $\tau^\pm \to \nu\pi^\pm\pi^+\pi^-$ decay and its interpretation as the $\tau^\pm \to \nu A_1 \to \nu\pi^\pm\pi^+\pi^-$ decay were recently presented by the PLUTO collaboration [9]. Data suggesting this decay mode have also been put forward by the SLAC-LBL collaboration [10]. In this letter we

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describe the observation of the $\tau \to \nu\rho\pi$ decay and discuss its possible interpretation as the $\tau \to \nu A_1$ decay mode. We also show that our data cannot be explained by charm production.

The data were taken with the PLUTO detector at the DESY e^+e^- storage ring DORIS. A total luminosity of 5600 nb^{-1} was accumulated at center of mass energies W of 3.6 GeV and between 4 and 5 GeV. The detector consists of a superconducting solenoid having a 2 T magnetic field parallel to the beam. The useful magnetic volume of 1.4 m diameter and 1.0 m length is filled with 14 cylindrical proportional wire chambers used both for triggering and track recording. In this way a total of $0.94 \times 4\pi$ geometrical acceptance is obtained for charged particles.

The detector contains two cylindrical lead converters of radii 38 and 59 cm which are centered on the beam axis and are respectively 0.44 and 1.70 radiation lengths thick. These lead layers are used to identify electrons and to detect photons. In this apparatus the detection efficiency of a π^0-meson amounts to 85%. Further details concerning the PLUTO detector and its performance have been presented elsewhere [11].

To investigate the τ-decay into three charged pions and a neutrino we have searched for single electron events satisfying the kinematics of the reaction

$$e^+e^- \to \tau^+\tau^- \to \nu\nu e^{\pm} + \nu\pi^{\mp}\pi^+\pi^- \quad (1)$$

with the final state signature of

$$e^+e^- \to e^{\pm}\pi^{\mp}\pi^+\pi^- + \text{missing mass.} \quad (2)$$

Tracks for which electron (positron) hadron separation is possible are called electron candidates. They have a production angle of $|\cos\theta| < 0.55$ and a momentum of $P_{\perp} \geqslant 0.2$ GeV/c transverse to the beam. The separation was achieved by a detailed analysis of the shower pattern, developed in the two proportional chambers behind the second lead converter. The separation method has a recognition efficiency for electrons of 30% at a momentum of $P_e = 0.4$ GeV/c and of 65% at $P_e \geqslant 1.0$ GeV/c. The probability for misidentifying a hadron as an electron was kept to (1.2 ± 0.2)% at all momenta. Because of the low efficiency for electron-hadron separation below 0.4 GeV/c, electron-candidate tracks in that momentum range were not used for further physics analysis.

A total electron-candidate sample of 3053 events was defined as all charge balanced 4-prong events with an electron candidate and a missing mass greater than 0.9 GeV [‡1]. From this we obtained an electron sample of 39 events each of which has an identified electron and no observed photon. The magnitude and kinematic distributions of background due to electron misidentification, and the amount of contamination by electron events with a missed photon, were obtained from studies of the remaining sample.

Since reaction (1) is kinematically underconstrained, no direct identification of events via a fit is possible. Therefore the assignment of events to reaction (1) is verified by determining that all observable features are consistent with this reaction.

First we note that none of the events is produced at $W = 3.6$ GeV. Then we show in fig. 1a the invariant mass of the three hadrons, interpreted as pions, plotted against the electron momentum P_e, for events produced in the W-range of 4.5 to 5.0 GeV. As is seen, the mass distribution of the three pions peaks at low mass around 1.1 GeV. The electron momentum on the other hand, is widely spread over the range from 0.4 GeV/c (lower cut-off value) up to 1.5 GeV/c. No correlation between $M_{3\pi}$ and P_e is observed. These features, which are also present in the data produced at $4.0 \leqslant W \leqslant 4.5$ GeV, are as expected for reaction (1).

From the electron sample of 39 events we select those events for which the 3π system has an invariant mass and momentum which are consistent with coming from the pair production and subsequent decay of a particle with a mass of $\leqslant$1.9 GeV. Only 6 events fail this selection. The 33 events in the consistent sample contain an estimated background of 13 ± 4 from hadrons misidentified as electrons, and at most 3 events which had unobserved photons.

In fig. 3a we show for the consistent events the distribution containing the two neutral $\pi^+\pi^-$ mass combinations, together with the background determined for misidentified electrons.

This distribution can be understood as arising mainly from a ρ-signal in one combination and a broad distribution arising from the other. The background expected from misidentified events does not show a ρ^0-signal. The shaded distribution with only one mass com-

‡1 The 4-prong events show a (missing mass)^2 peak at 0.0 GeV^2. The missing-mass cut was chosen to remove the events in this peak because they are not candidates for reaction (1) which involves 3 missing neutrinos.

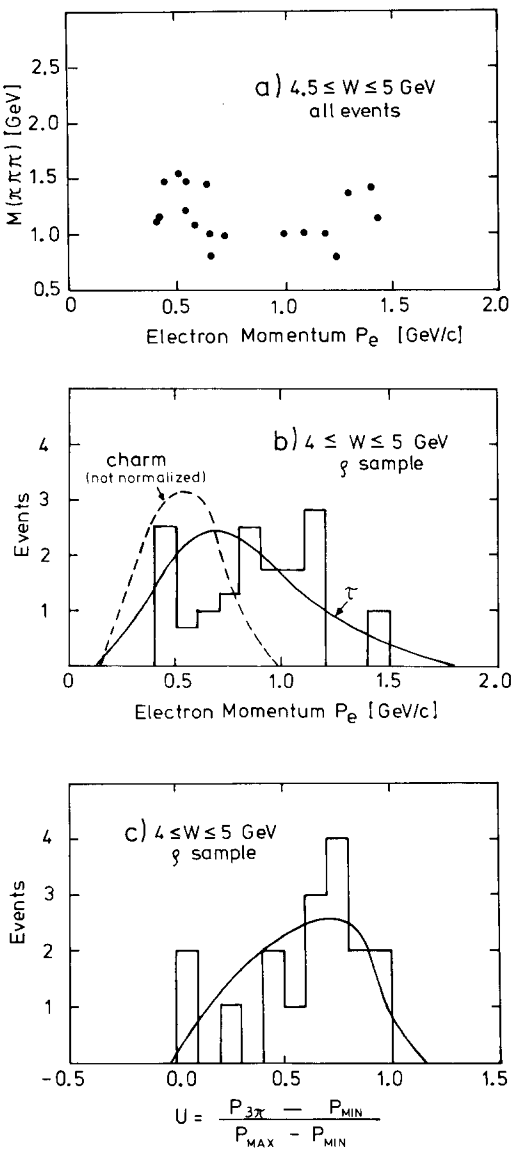

Fig. 1. Kinematic properties of the $e\pi\pi\pi$ events relevant to the $\tau^+\tau^-$ lepton pair assignment. a) Invariant mass of the 3π-system plotted against the electron momentum P_e in the CMS energy interval 4.5 to 5 GeV. b) The electron-momentum distribution for events from the ρ-sample (see text). The background expected from hadron electron misidentification is subtracted. The solid curve is the prediction for τ-decay (normalized to the data for $P_e > 0.4$ GeV/c). The dashed curve shows the shape expected from charmed particle production based on data from ref. [13]. The curves are corrected for detection efficiency. c) Distribution of the normalized 3π-momentum U (ρ-sample), compared with the expected $\tau \to \nu\pi\pi\pi$ decay distribution folded with the experimental resolution and acceptance.

bination, namely the larger one, shows the ρ-signal more clearly. We conclude that we have evidence for a clear $e\pi\pi\pi$ signal for events consistent with reaction (1) and that they are strongly associated with ρ^0-production. In fact, as we show later, the events exceeding the calculated background, are quantitatively consistent with coming from the reaction

$$e^+e^- \to \tau^+\tau^- \to \nu\nu e + \nu\rho^0\pi . \qquad (3)$$

On the other hand, the 6 events kinematically inconsistent with reaction (1) show no ρ-signal (fig. 3b). Moreover, they are well accounted for by the calculated background and we therefore exclude them from further analysis.

For the purpose of testing further that the $e\pi\pi\pi$ events are due to τ-production we limit ourselves to a ρ^0-sample of 21 events (events with at least one $\pi^+\pi^-$-mass combination between 0.70 and 0.84 GeV) since there the expected background amounts to only 20% of the observed events, as compared to 75% in the non-ρ sample (12 events).

Next we study the laboratory momentum $P_{3\pi}$ of the 3π system. For a 2-body production process, $e^+e^- \to \tau^+\tau^-$ and a subsequent decay, $\tau \to \nu(3\pi)$, where the center of mass energy W and the 3π mass $M_{3\pi}$ are fixed, $P_{3\pi}$ is uniformly distributed between the limits P_{min} and P_{max}. These limits depend on W and $M_{3\pi}$. However, the quantity $U = (P_{3\pi} - P_{min})/(P_{max} - P_{min})$ is uniformly populated in the range of 0 to 1 for any set of W and $M_{3\pi}$ values. In fig. 1c we compare our experimental U-distribution with the expected one from reaction (3) (solid curve) calculated by the Monte-Carlo method. The experimental acceptance and resolution were included. Good agreement between the data and the calculated curve is seen. Additional related evidence for τ-production is given by the angular distribution of the electrons with respect to the 3π system. This distribution is shown in figs. 2a and 2b, respectively, for events produced in the W-range of (4.0 to 4.5) and (4.5 to 5.0) GeV. As can be expected, these distributions tend to peak more in the backward direction as W increases. Again, the data and the Monte-Carlo calculation for reaction (3) (solid curve) are in good agreement. As a third check, we compare in fig. 1b the experimental electron-momentum distribution with that expected [12] for a V–A decay of the τ (solid line) and find good agreement. Thus all three distributions confirm the hypothesis that the signal is due to τ-production and subsequent decay.

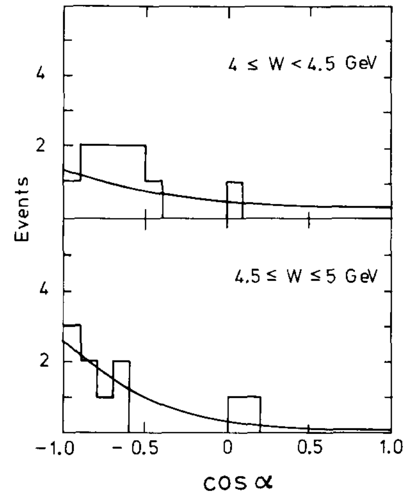

Fig. 2. The cos α (collinearity) angular distribution of the electrons with respect to the 3π-system for the ρ-sample. The solid lines represent the expected distributions for the $e^+e^- \to \tau^+\tau^- \to \nu\nu e + \pi\pi\pi\nu$ reaction normalized to the data.

Having verified the assignment of our data to the $e^+e^- \to \tau^+\tau^-$ process, we return to the analysis of the two- and three-pion mass systems ‡2 shown in figs. 3a, c and d. The 3π-mass distribution of the 21 events with at least one $\pi^+\pi^-$ in the ρ-mass band is shown in fig. 3c together with the distribution of the background of 4 to 5 events expected from misidentified electrons. The mass histogram shows a clustering consistent with the mass and width reported for the A_1-meson [7,8]. For comparison we show in fig. 3d the 3π-mass distribution for the 12 events with no $\pi^+\pi^-$-mass combination in the ρ-band. This distribution shows no resonance structure and is well described by the expected background of 9 events.

To estimate the $\rho\pi$-content of the events in excess of the background (figs. 3c and d), we generated 3π-states with an invariant mass spectrum proportional to

‡2 We cannot rule out the possibility that some of these charged tracks are kaons. However, we assume that τ-decays into strange particles are suppressed due to the Cabibbo angle. Experimental support for this assumption has been obtained recently [13].

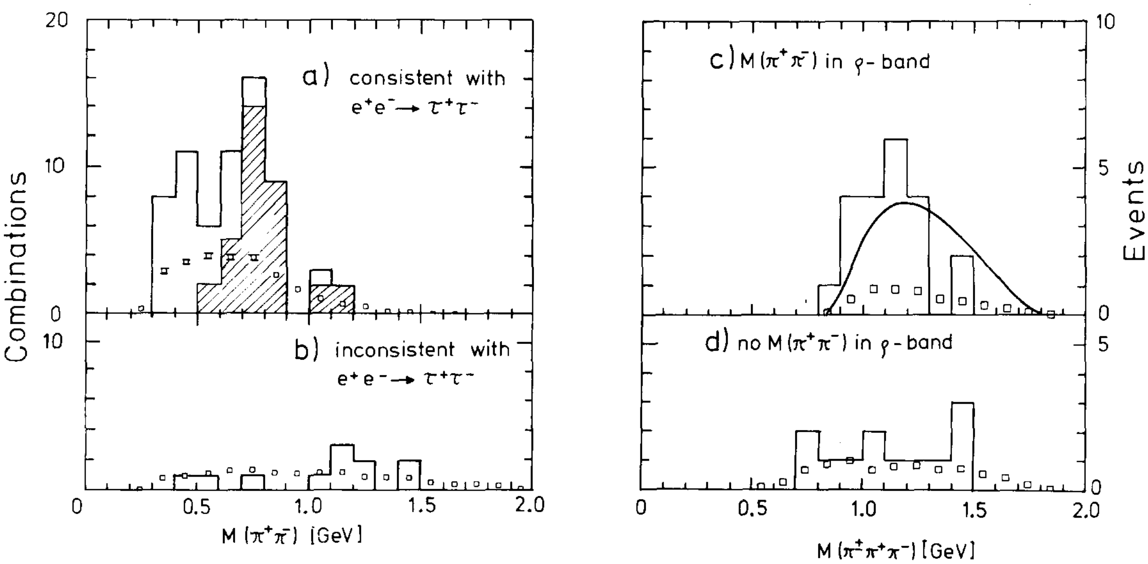

Fig. 3. Two and three pion mass distributions. a) $M(\pi^+\pi^-)$ for events kinematically consistent with the $e^+e^- \to \tau^+\tau^-$ reaction, with two combinations per event. Shaded area represents the distribution of the higher $M(\pi^+\pi^-)$ combination. b) $M(\pi^+\pi^-)$ for events kinematically inconsistent with the $e^+e^- \to \tau^+\tau^-$ reaction. c) $M(\pi^\pm\pi^+\pi^-)$ distribution for events consistent with the $e^+e^- \to \tau^+\tau^-$ reaction and having at least one $M(\pi^+\pi^-)$ in the ρ-band. d) $M(\pi^\pm\pi^+\pi^-)$ distribution for events consistent with the $e^+e^- \to \tau^+\tau^-$ reaction and no $M(\pi^+\pi^-)$ combination in the ρ-band. The squares represent the expected distributions for background from misidentified events. The solid line in c) represents the sum of the background and $\tau \to \rho^0\pi$ decay distribution normalized to the data.

Table 1

CMS energy (GeV)	Integrated luminosity (nb^{-1})	Observed $e\pi\pi\pi$ events (ρ-cut)	Expected misidentified events	Cross section a) (pb)	$B(e\nu\nu)\cdot B(\nu\rho^0\pi)$ b)	$B(\nu\rho^0\pi)$ c)
3.6	635	0	<1	–	–	–
4.0–4.5	2850	11	2.5	37 ± 14	0.0077 ± 0.0030	0.050 ± 0.015
4.5–5.0	2200	10	2	55 ± 19	0.0090 ± 0.0033	

a) With acceptance corrections for $e^+e^- \to \tau^+\tau^- \to (e\nu\nu) + (\nu\rho^0\pi)$. There is a 30% systematic uncertainty in this correction, which also applies to the subsequent branching ratios.
b) Using a τ-mass of 1.9 GeV for calculating $\sigma(e^+e^- \to \tau^+\tau^-)$.
c) Using a branching ratio of $B(e\nu\nu) = 0.16$. With $m_\tau = 1.8$ GeV [see b)] we arrive at $B(\nu\rho^0\pi) = 0.045 \pm 0.013$.

the observed distribution. For an uncorrelated 3π-decay of these states we calculate that the expected ratio between events outside the ρ^0-band to those inside is 2.5, in total disagreement with the experimental value of 0.2 ± 0.2. On the other hand a $\rho\pi$-decay of these states implies for the same ratio a value of 0.3 which is quite consistent with the data. We thus infer an upper limit of 20% (with 95% confidence level) for the uncorrelated 3π-contribution to the events shown in figs. 3c and d.

Finally, we address the question of whether the shape of the $\rho\pi$-mass distribution provides evidence for the A_1-meson. To this end we calculate the shape of the $\rho\pi$-mass distribution as expected for a (V–A) weak interaction decay process [14] $\tau \to \nu$ + non resonant ($\pi\rho$). Fig. 3c shows this distribution, added to the background. The probability that this decay mode (without an A_1-resonance) fits the data is about 5% when using a conservative ‡3 value of $m_\tau = 1.80$ GeV, and $m_\nu = 0$ GeV. The probability increases when taking the $\rho\pi$-system to be in the A_1-resonance, e.g. we find 80% with typical A_1-parameters of $m_{A_1} = 1.1$ GeV and $\Gamma_{A_1} = 0.25$ GeV. We thus conclude that while the 3π-mass distribution is consistent with $\tau \to \nu$ + nonresonant ($\pi\rho^0$), the decay interpretation $\tau \to \nu + A_1 \to \nu + (\pi\rho^0)$ is favoured.

In table 1 we summarize our results for $e^+e^- \to \nu\nu e + \nu\rho^0\pi$. The branching ratio $B(\tau \to \nu\nu e)\cdot B(\tau \to \nu\rho^0\pi)$ is obtained by using a τ-mass of 1.9 GeV in the calculation of the heavy lepton cross section. The values for this branching ratio agree in the two energy regions of the data. For calculating the branching ratio for $\rho^0\pi$ we used $B(\tau \to \nu\nu e) = 0.16$ [3,9]. The values quoted in the table have a systematic uncertainty of 30%.

‡3 The value of 1.8 GeV is one standard deviation below the current average [10]. The choice is conservative with respect to the A_1, since it favours the non-resonant interpretation.

Finally we consider the interpretation of our data in terms of charm. The production and subsequent decay of charmed particles may also lead to the final state e + 3 prong + no shower. First we note that in our events the electron and any of the other three particles cannot come from the decay of the same charmed particle, because of their kinematic properties discussed above. Hence we have as background sources the combined charm decays $D^+ \to e^+\nu K^0_L$ and $(D^{*-}, D^-) \to (K^+\pi^-\pi^-, K^+\pi^-\pi^-\pi^0$ and $\pi^+\pi^-\pi^-K^0_L)$, and charge conjugates where the K^0_L-particles escape the detector. The first of the hadronic D-decay modes can be ruled out completely since in none of the events do the 3 charged tracks, with proper mass assignments, yield effective D- or D^*-masses. The second decay should yield 5 to 6 times as many events of the type e + 3 prong + shower as without showers. From the observed rate with showers we infer that less than 2 events can come from this source. The contribution of the third decay can be estimated from the known decay branching ratios [15] of D-mesons to be less than 1 event. Since the decay $F^+ \to e^+$ + (no tracks, no showers) is predicted [16] to be very rare, we expect less than 1/4 of an event from F-production among the observed events. The absence of any considerable charm contamination is supported by our electron-momentum distribution (fig. 1b) which does not agree with a measured spectrum of electrons attributed to charm [13].

In conclusion we have observed clear evidence for the $e^-e^+ \to \tau^+\tau^-$ production in its $\nu\nu e + \nu\rho\pi$ decay configuration yielding a branching ratio $B(\tau^+ \to \nu\rho^0\pi^+) = 0.050 \pm 0.015$. An alternative interpretation in terms of charm-anticharm production can safely be ruled out. The observation of a negative G-parity hadronic state, like $\rho\pi$, implies under the assumption of only first class V or A currents that the τ-leptonic weak current couples to a hadronic weak axial current. The mass distributions are entirely consistent with the $\tau \to \nu A_1$ decay mode. The branching ratio for a V–A decay of a sequential heavy lepton into A_1 has been predicted [2] to be 0.07, consistent with our result of 0.10 ± 0.03 when taking $B(\tau^+ \to \nu A_1^+) = 2B(\tau^+ \to \nu\rho^0\pi^+)$. For the decay $\tau^\pm \to \nu$ + uncorrelated $(\pi^\pm\pi^+\pi^-)$ we find an upper limit to the branching ratio of 0.01. Finally we note that the τ-decays studied here do not seem to saturate the branching ratio of 0.3 ± 0.1 measured [3] for multiprong decays.

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