PRODUCTION AND PROPERTIES OF THE τ-LEPTON IN e^+e^- ANNIHILATION AT C.M. ENERGIES FROM 12 TO 31.6 GeV

TASSO Collaboration

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We have observed τ production in e^+e^- annihilation at centre-of-mass energies between 12 and 31.6 GeV with cross sections in agreement with the QED τ-pair cross section. Branching ratios for τ decay have been measured and are consistent with the world averages. We have determined the cutoff parameters of QED Λ_+ (Λ_-) to be > 73 GeV (82 GeV) and have obtained an upper limit on the τ lifetime of 1.4×10^{-12} s (95% CL).

In this letter, we report on the observation of τ production in the TASSO detector in the PETRA e^+e^- storage ring at DESY. Data have been taken at centre-of-mass energies between 12 and 31.6 GeV. At these energies tests of the τ's lifetime and its QED behaviour can be made more stringent than was previously possible. The detection of the τ is also facilitated since many of its decay modes result in distinctive low multiplicity topologies.

The main features of the central detector have been described previously [1]. A view of the entire detector along the beam direction is shown in fig. 1. The magnet provides a 5 kG magnetic field. Particle measurement close to the interaction vertex is provided by four cylindrical proportional chambers, each layer having 480 wires in azimuth. Charged particles are tracked through fifteen layers of drift chambers, nine with sense wires parallel to the beam axis and six with wires oriented at $\approx \pm 4°$; these chambers have a position resolution of 250 μm. Using the central detector system and the analysis procedure for charged tracks described in previous publications [2], a momentum resolution of $\sigma_p/p \approx 0.02p$ (p in GeV/c) is obtained.

Electrons and photons are identified by their electromagnetic showers in an array of lead–scintillator sandwich shower counters, nine radiation lengths thick, which cover 52% of the solid angle. The light emitted by the passage of a charged particle through the scintillator is collected by wavelength shifter bars and channelled into photomultipliers. The counters have an energy resolution σ_E/E = 14% averaged over the range $2 \leqslant E \leqslant 15$ GeV. Electrons which hit within 10 cm from the edge of a counter or shower in the coil have σ_E/E = 18%. Electrons with $E > 2$ GeV are identified by requiring that the difference between their measured shower energy and their momentum is less than three standard deviations. The probability that an isolated hadron is identified as an electron by this

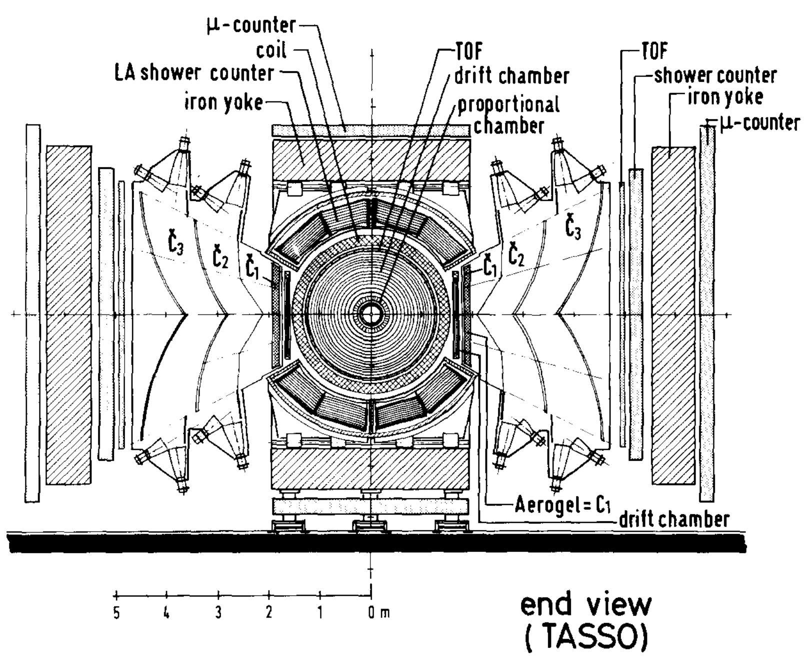

Fig. 1. View of the TASSO detector along the beam line.

criterion varies from 2.2% for particles with $E = 2$ GeV to 0.5% for $E \geqslant 4$ GeV. We do not attempt to identify electrons with energy less than 2 GeV.

Muons penetrating through iron absorber are identified by their signals in four layers of proportional tubes measuring two orthogonal coordinates. The tubes are 4 cm × 4 cm in cross section, and are offset to give a resolution of 6 mm. The iron thickness in front of the tubes is 80 cm in the iron yoke of the flux return (19% of the 4π), 87 cm in the hadron arms (13% of the 4π) and 50 cm over the end caps (13% of 4π, reduced by the trigger in the work described here to an effective solid angle of 9% of 4π). In addition the muons traverse the shower counters which are equivalent to 10 cm of iron. Particles are tagged as muons if they give hits in at least three proportional tube layers within 3 standard deviations of the extrapolated track position. The position uncertainty included tracking resolution and multiple scattering in the iron. Muons of momentum less than ≈ 1 GeV/c do not penetrate the iron. Above 2 GeV/c, the tagging efficiency is greater than 99% and the pion contamination probability from decay in flight and punch through is 2% per track.

The trigger used to detect τ events depended on the centre-of-mass energy W. At 12 GeV, the trigger required $\geqslant 2$ charged tracks with a transverse momentum $\geqslant 0.20$ GeV/c. The transverse momentum cutoff was increased to $\geqslant 0.32$ GeV/c for higher energies. The trigger required $\geqslant 3$ charged tracks for W between 13 and 17 GeV, $\geqslant 4$ tracks for $W > 17$ GeV. In addition, at all energies a "back-to-back" trigger was included which required $\geqslant 2$ charged tracks coplanar with the beam axis to within 27°.

The luminosity was determined both from small-angle and wide-angle Bhabha scattering events [3]. The two methods agreed to within the systematic uncertainty of the small-angle detector, which was estimated to be +5%, –8%.

We first discuss the reaction

$$
\begin{aligned}
e^+e^- \to\ & \tau \\
& \hookrightarrow 1 \text{ charged particle + neutrals} \\
+\ & \tau \\
& \hookrightarrow 1 \text{ charged particle + neutrals.}
\end{aligned}
$$

To select these events we used only the data around 30 GeV [4] restricting the analysis to the region with charged and neutral particle identification, including muon identification, covering 30% of 4π. These data correspond to an integrated luminosity of 1867 nb^{-1}.

Events were required to have

(a) two oppositely charged tracks reconstructed in three dimensions,

(b) the momentum of each track greater than 2 GeV/c,

(c) an acolinearity angle between 2.5° and 90° in three dimensions and greater than 1° in the plane perpendicular to the beam axis.

Cut (c) reduces the background from $e^+e^- \to e^+e^-$, $e^+e^-\gamma$, $\mu^+\mu^-$ events. For all topologies investigated, tracks were classified according to the electron and muon identification criteria described above. A track was considered to be a hadron if it was inconsistent with being a muon and gave energy in the shower counters more than three standard deviations away from that expected for an electron of that momentum. If the energy of a shower, associated with a charged hadron, was larger than expected from a minimum ionizing particle (by more than three standard deviations), the shower counter was considered to have also detected a photon. If the energy of a shower not associated with a charged track exceeded 1 GeV, it was assumed that at least one photon had been produced in the reaction.

All events satisfying the 1 + 1 topology selection criteria were scanned. In order to reduce background from $e^+e^- \to e^+e^-$, $e^+e^-\gamma$, $\mu^+\mu^-$ events, those in which both tracks were identified as electrons or both as muons were removed. After these cuts, 5 τ-pairs were found.

The background from beam gas interactions to τ events of all topologies was investigated using events occurring between 10 cm $\leqslant |z| \leqslant$ 30 cm, where the z coordinate lies along the beam direction. For all τ topologies this background was found to be negligible.

The background from two-photon processes was investigated using a Monte Carlo generator ‡1. Using the cuts described above, the two-photon background was also found to be negligible.

Contamination from e^+e^- annihilation into hadrons was estimated, for all decay topologies, with a

‡1 We are grateful to Dr. J.A.M. Vermaseren, CERN, for providing his Monte Carlo program.

Field–Feynman type Monte-Carlo program [5] [‡2] including u, d, s, c, b quarks and gluon effects. For the 1 + 1 topology the background was negligible.

The second topology we investigated was

$$e^+e^- \to \tau \quad \hookrightarrow 1 \text{ charged particle} + \text{neutrals}$$
$$+\ \tau \quad \hookrightarrow 3 \text{ charged particles} + \text{neutrals},$$

where the single charged particle was separated by more than 90° from the remaining three and a net charge of zero was demanded. This topology was used to isolate τ events without the requirement of lepton identification. We studied all events with W between 12 and 31.6 GeV having $\Sigma_i |p_i|$ (sum of the visible charged momenta) > 4 GeV/c (5 GeV/c) for $W \leqslant 13$ GeV ($\geqslant 17$ GeV). The data correspond to an integrated luminosity of 2973 nb^{-1}.

Of the events thus selected, by far the largest number came from radiative Bhabha scattering where the photon converted before the central drift chamber. In order to reduce the number of events from this process we made a cut on the effective mass (m_{+-}) of charge zero pairs of particles within the group of three. Assuming both particles to be electrons, the lower of the two m_{+-} combinations was strongly peaked near zero. We excluded all events with $m_{+-} < 150$ MeV, leaving 55 candidates for $\tau^+\tau^-$ production. It was verified that for each three-prong the effective mass was consistent with originating from a τ. We estimated the residual background from radiative Bhabha scattering using a Monte-Carlo calculation and by extrapolating the observed m_{+-} spectrum beyond 150 MeV. Both methods gave a background of 3 ± 2 events.

The remaining backgrounds in this topology were from two-photon processes and from e^+e^- annihilation into hadrons. To estimate the contamination from the first process we examined events passing the topology selection but failing the $\Sigma_i |p_i|$ cut described previously. The number of events peaks at very low values of $\Sigma_i |p_i|$ and falls off sharply with increasing $\Sigma_i |p_i|$. The two-photon contamination of the τ sample was found to be negligible. The contamination from e^+e^- annihilation into hadrons was estimated to be $\leqslant 4$ events.

‡2 The branching ratios for B-meson decay were taken from Ali et al. [6].

We also studied the reaction

$$e^+e^- \to \tau \quad \hookrightarrow 3 \text{ charged particles} + \text{neutrals}$$
$$+\ \tau \quad \hookrightarrow 3 \text{ charged particles} + \text{neutrals},$$

which was selected by requiring two groups of three particles in well-separated jets in opposite hemispheres. A net charge of zero was demanded for each event, with each jet having charge of either +1 or −1. Events having any m_{+-} combination < 150 MeV (considering the particles to be electrons) were rejected, as were events with a three pion effective mass > 2.0 GeV. Because hadronic background increases below $W = 17$ GeV, the six-prong events were only isolated for $W > 17$ GeV. Eight τ pairs were found with an estimated contamination from all background processes of < 2 events.

Finally we have attempted to isolate the decay mode $\tau \to 5$ charged particles + neutrals. From the data at ≈ 30 GeV we found 2 candidates for the topology

$$e^+e^- \to \tau \quad \hookrightarrow 1 \text{ charged particle} + \text{neutrals}$$
$$+\ \tau \quad \hookrightarrow 5 \text{ charged particles} + \text{neutrals},$$

which is consistent with the expected hadronic background of ≈ 2. Assuming both candidates come from τ decays, we place an upper limit on the branching ratio ($\tau \to 5$ charged particles + neutrals) < 0.06 (95% CL).

We have used the observed τ leptons, corresponding to the 1867 nb^{-1} around $W = 30$ GeV to calculate topological branching ratios. We assumed that the acceptance corrected topological branching ratios $\tau\bar{\tau} \to 1 + 1$ prongs, $\tau\bar{\tau} \to 1 + 3$ prongs and $\tau\bar{\tau} \to 3 + 3$ prongs sum to 1. We have used a maximum likelihood fit to calculate the branching ratios (BR) ($\tau \to 1$ charged particle + neutrals) and ($\tau \to 3$ charged particles + neutrals). Using the four-prong events we have also performed maximum likelihood fits to determine the branching ratios into $\mu\nu\bar{\nu}$, $e\nu\bar{\nu}$, one charged hadron + $\geqslant 0$ photons + ν, three charged hadrons + ν, and three charged hadrons + $\geqslant 1$ photon + ν, where we have made use of the particle identification criteria described above. The sum of the branching ratios into $\mu\nu\bar{\nu}$, $e\nu\bar{\nu}$ and one charged hadron + $\geqslant 0$ photons + ν was constrained to equal the BR ($\tau \to 1$ charged particle + neutrals). The sum of BR ($\tau \to 3$ charged hadrons + ν) and BR ($\tau \to 3$ charged hadrons + $\geqslant 1$ photon + ν) was constrained to equal BR ($\tau \to 3$ charged particles + neutrals). These measurements, which are summarized in table 1, are in good agreement with world average values [7] and theoretical expectations [7,8].

Using the 1 + 3 topology events, which are the cleanest and most abundant, we have calculated the acceptance corrected τ cross section at energies between 12 and 31.6 GeV assuming the world average branching ratio of $\tau^+\tau^- \to 1 + 3$ prongs of 0.37 ± 0.04 [7]. The result is shown in fig. 2, where the measured points have been radiatively corrected by adapting the procedure of Berends et al. [9]. The curve shows the τ-pair cross section predicted by QED. The calculated and measured cross sections are in agreement.

We have used our measured cross sections to test QED. Defining $\Lambda_\pm$ such that

$$\sigma_\tau = \sigma_{\mathrm{QED}}[1 \pm s/(s - \Lambda_\mp^2)]^2, \quad s = W^2,$$

we have determined $\Lambda_+ > 73$ GeV, $\Lambda > 82$ GeV to 95% confidence level, agreeing with earlier evidence from DORIS [10] and PETRA [11] that the τ is a point-like particle.

In order to study the angular distribution of τ pair production, we show in fig. 3a the acceptance corrected distribution of the cosine of the average angle of the decay systems from each τ, relative to the beam direction. We have plotted the 1 + 3 and 3 + 3 prong events from all our data. The curve in fig. 3a shows the result of a maximum likelihood fit of the form

$$\mathrm{d}N/\mathrm{d}\cos\theta \propto 1 + A\cos^2\theta .$$

A is found to be 1.2 ± 0.9, consistent with $A = 1$ as expected for a spin-1/2 particle.

An important test of lepton universality is the measurement of the τ lifetime, which is predicted to be around 3×10^{-13} s [8], giving a decay length of about 0.7 mm at $W = 30$ GeV. Several methods have been used in the past to find limits for the τ lifetime [12,13]. The previous best upper limit is 2.3×10^{-12} s (95% CL) given by the DELCO group [13]. For our

Table 1

	No. of events a)		This experiment	World average [7]	Theory [7,8]
	A	B			
Topological branching ratios					
1 + 1 prongs	5	5	0.51 ± 0.12 b)	0.44 ± 0.04	0.55
1 + 3 prongs	55	27	0.44 ± 0.12	0.37 ± 0.04	0.38
3 + 3 prongs	8	4	0.05 ± 0.03	0.08 ± 0.03	0.04
1 + 5 prongs	2	2 ± 2	< 0.09 (95% CL)		
Branching ratios					
$\tau \to 1$ prong			0.76 ± 0.06	0.66 ± 0.04	0.74
$\tau \to 3$ prongs			0.24 ± 0.06	0.28 ± 0.06	0.26
$\tau \to 5$ prongs			< 0.06 (95% CL)		0.01
$\tau \to \mu\nu\bar{\nu}$			0.35 ± 0.14	0.18 ± 0.01	0.175
$\tau \to e\nu\bar{\nu}$			0.19 ± 0.09	0.17 ± 0.01	0.18
$\tau \to 1$ charged hadron + $\geqslant 0$ photons + ν			0.22 ± 0.14	0.30 ± 0.04	0.44
$\tau \to 3$ charged hadrons + ν			0.09 ± 0.06	0.06 ± 0.01	0.04
$\tau \to 3$ charged hadrons + $\geqslant 1$ photon + ν			0.15 ± 0.07	0.11 ± 0.07 c)	0.14

a) Column A: Number of events observed at all energies (background not subtracted). Column B: Number of events observed around $W = 30$ GeV (background subtracted). These numbers have been used to determine the branching ratios.

b) The errors on the branching ratios are lower than the statistical errors due to the constraint that the sum of the branching ratios should equal 1. Systematic errors are estimated to be much smaller than the statistical errors.

c) This number is from ref. [14] and is not a world average.

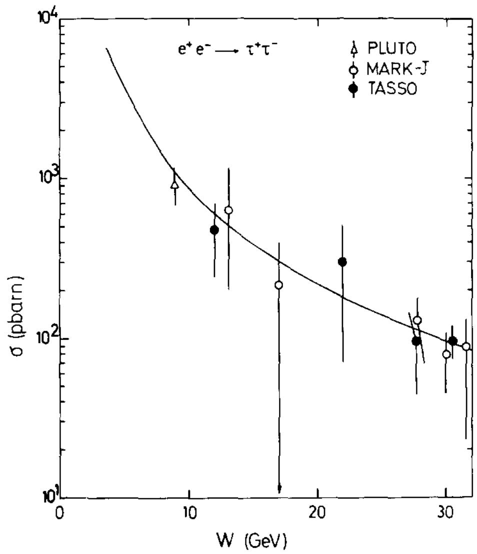

Fig. 2. The cross section for the process $e^+e^- \to \tau^+\tau^-$ from this experiment (•) and from refs. [10] (△) and [11] (○). The data have been radiatively corrected. The curve shows the QED prediction for $\sigma(e^+e^- \to \tau^+\tau^-)$. The error bars include statistical effects and the uncertainty on the topological branching ratio $\tau\bar{\tau} \to 1 + 3$ prongs. An additional overall systematic error of $\approx 10\%$ is not included.

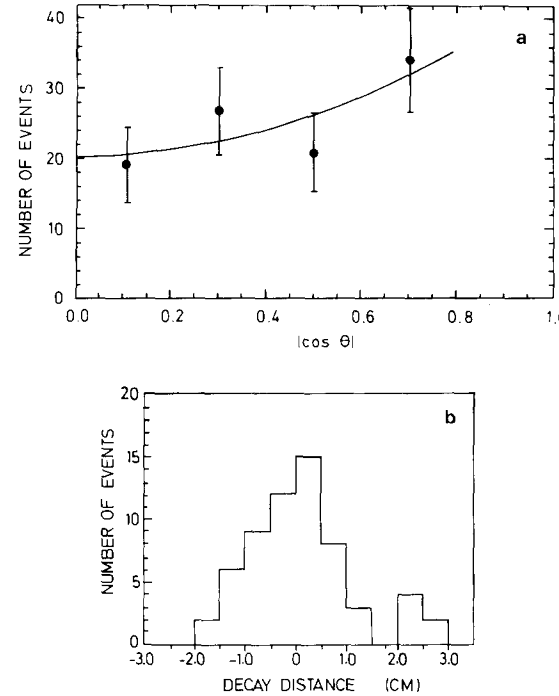

Fig. 3. (a) The angular distribution of the τ production direction for all data. The curve is a best fit of the form $1 + A \times \cos^2\theta$ to the data, giving $A = 1.2 \pm 0.9$. (b) The distribution of three-prong vertices around the centre of the beam spot from events with $\tau \to 3$ charged particles + neutrals. The projection of the decay length perpendicular to the beam axis is plotted.

total sample of four- and six-prong $\tau\bar{\tau}$ candidates we calculated the intersection of the three hadrons from the decay of one of the τ's in the plane perpendicular to the beam axis. The decay length is defined as the distance between the intersection point and the centre of the beam spot. The beam position was determined using Bhabha and hadronic events over several groups of runs; it had an error on the mean of ≈ 0.15 mm in x and y. We show in fig. 3b the distribution of the decay length, which is negative for intersection points on the opposite side of the origin from the three-particle momentum direction. The distribution is approximately gaussian centered on zero as would be expected for a τ with a decay length smaller than our spatial resolution (≈ 1 cm). The decay length was converted into three dimensions using the z-component of the resultant of the three-prong momentum vectors. The decay time was then calculated assuming the τ to have energy equal to the beam energy. The mean lifetime was found to be $(0.16 \pm 0.72) \times 10^{-12}$ s, which corresponds to an upper limit on the τ lifetime of 1.4×10^{-12} s with 95% confidence. This number can be converted into a lower limit for the strength of the τ–ν_τ coupling to the weak current, g_τ. We find that $g_\tau \geqslant 0.46\, g_e$, where g_e is the e–ν_e coupling.

In summary, we have isolated τ events of various topologies produced in e^+e^- annihilations between $W = 12$ and 31.6 GeV. We find cross sections in agreement with QED predictions and branching ratios consistent with the world averages. We have improved the upper limit on the τ lifetime to 1.4×10^{-12} s. At high energies, the properties of the τ are consistent with those expected from a sequential point-like lepton described by standard models of the weak and electromagnetic interactions.

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