Measurement of the Threshold Behavior of $\tau^+\tau^-$ Production in e^+e^- Annihilation

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We have observed 692 events of the type $e^+e^- \to e^\pm X^\mp$ $(X \neq e)$ in the center-of-mass energy range 3.1 GeV $< E_{\text{c.m.}} <$ 7.4 GeV. The observation of events below $D^0\bar{D}^0$ threshold clearly precludes their association with charm. The data are well fitted by a pointlike spin-$\frac{1}{2}$ τ lepton with mass 1782^{+2}_{-7} MeV, electronic branching ratio 0.160 ± 0.013, and branching ratio to ≥ 3 charged particles 0.32 ± 0.05.

Since the original observation by Perl *et al.*[1] of anomalous $e\mu$ events in e^+e^- annihilation, evidence[2] has accumulated that they result from the production and decay of a pair of heavy leptons, $\tau^+\tau^-$. Since τ decays mainly yield single charged particles,[3] the primary evidence comes from the $e\mu$ final state and the inclusive "anomalous" two-prong lepton events, $e(\mu)X$, $X \neq e(\mu)$. The proximity of the thresholds for these events and for charmed particle production makes it imperative to exclude the charm interpretation of their origin. A keystone of the argument against charm has been the observation[2,4] of a cross section consistent with pointlike production. We present in this Letter a detailed cross-section measurement, emphasizing the threshold region, based on a large sample of eX events with low background and a broad electron momentum acceptance (P_e >0.2 GeV/c).

The data were obtained at SPEAR using the DELCO detector. The apparatus, described previously,[5] consists of a set of cylindrical multiwire proportional chambers (MWPC) and a threshold Cherenkov counter, sensitive only to electrons, followed by spark chambers and shower counters. The latter consist of three layers of Pb (6 radiation lengths total) and three layers of scintillator viewed by individual phototubes. These components subtend 60% of the full solid angle. Charged particles are tagged over 95% of the solid angle by means of the MWPC and pie-shaped (P) counters covering the region between 15° and 35° relative to the beam axis. A magnet provides 3.5 kG over the MWPC volume and allows a momentum measurement accuracy $\Delta P/P = 8(P/\text{GeV})\%$.

The accepted eX events were required to have two and only two tracks of opposite charge, both with an associated shower counter pulse exceeding 0.3 minimum-ionizing particle (mip) and deviating from collinearity by at least 20° when viewed along the beam axis. In addition one particle had to be identified as an electron by an in-time Cherenkov pulse in the appropriate cell and the other as not an electron by the absence of such a pulse. The efficiency of the Cherenkov counter as a function of electron momentum reaches its asymptotic value of about 94% at 300 MeV/c and drops to zero at about 100 MeV/c. We therefore allowed a minimum momentum of 0.2 GeV/c for the electron and of 0.3 GeV/c for the X particle. Finally, events were rejected if they had an in-time P-counter tag.

The presence of a photon was indicated by a pulse in a shower counter unassociated with any charged track, whose total pulse height exceeded 3 mips. We rejected events consistent with the process $e^+e^- \to e^+e^-\gamma$ (presumably remaining in the sample due to a mixed Cherenkov tag). The number of events satisfying these requirements is 840 of which 535 have no photons.

We will now consider the residual backgrounds, firstly due to particle misidentification. Since the tracks are identified solely by the Cherenkov counter, the observed shower-counter pulse heights (Fig. 1) provide an independent determination of the particle nature. The electron pulse-

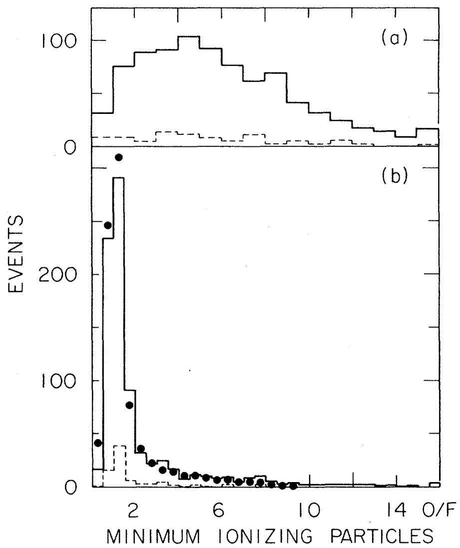

FIG. 1. (a) Shower-counter pulse-height distribution for electrons in the eX events. (b) Pulse-height distribution for the X particle. The dots indicate the pulse heights expected from a sample of 33% μ's and 66% π's. The dashed histograms were obtained at center-of-mass energies below charm threshold.

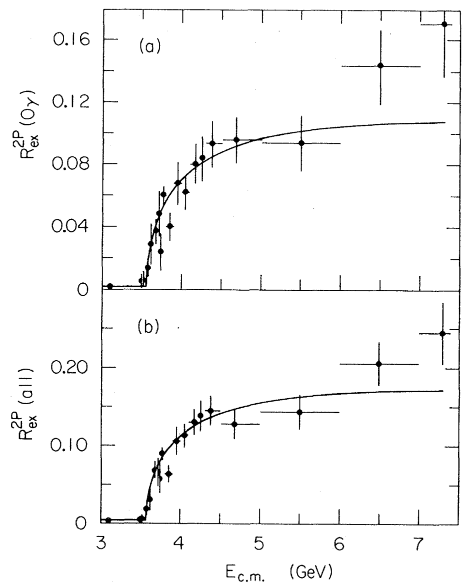

FIG. 2. (a) The production cross-section ratio, $R_{eX}{}^{2P}$, for eX events with no detected photons. Where data were not taken at a fixed beam energy the full range is indicated by horizontal error bars. The fit (χ^2 per degree of freedom = 17.3/15) indicates the cross section expected from a spin-$\frac{1}{2}$ τ lepton. (b) $R_{eX}{}^{2P}$ for all eX events (χ^2 per degree of freedom = 17.1/15). Both fits have excluded the ψ'' point (3.75 GeV < $E_{c.m.}$ < 3.80 GeV) because of possible charm contamination.

height distribution shows no evidence of any nonshowering particles but the enhanced tail on the X distribution betrays a 10% contribution from misidentified electrons. Accordingly a requirement of less than 3.3 mips is made on the X particle. This results in a loss of 12% of real events and a final data sample of 692 events of which 459 have no photons. From Fig. 1 we estimate the background from particle misidentification to be less than 28 events. This estimate has been confirmed by selecting either e^+e^- or X^+X^- events which satisfy all the other cuts except for the pulse-height cut.

The feed-down from the two photon interaction, $e^+e^- \to e^+e^-\mu^+\mu^-$, has been measured as $< 2 \pm 0.5\%$ by counting the events with same-sign tracks in agreement with an independent calculation.[6] An upper limit both on this background and on that due to particle misidentification has been obtained from data at $E_{c.m.} = 3.10$ (ψ), 3.50, and 3.52 GeV.

The production cross-section ratios, $R_{eX}{}^{2P}$ $[\sigma(e^+e^- \to eX)/\sigma(e^+e^- \to \mu^+\mu^-)]$, for eX events with no detected photons are shown in Fig. 2(a) and for all eX events in Fig. 2(b). The normalization is made to wide-angle Bhabha pairs (e^+e^-) except at the ψ and ψ' where we use $\mu^+\mu^-$ pairs (in order to account for the vacuum-polarization enhancement of the single-photon propagator). The data were corrected for the detection efficiency which varies by less than 2% up to $E_{c.m.} = 4.5$ GeV.

We now discuss a third potential background, charmed-particle decays. We first demonstration that the eX events are indeed observed below charm threshold (3726 ± 1.8 MeV). A comparison of the 70 events observed in the range[7] 3.57 GeV $\leq E_{c.m.} \leq 3.72$ GeV with those at higher energies in terms of rate, angular and momentum distributions, and associated photons shows both sets of data to be consistent with the hypothesis of a common origin. For example, the fraction of low-energy events containing photons is $(34 \pm 7)\%$ as compared with $(34 \pm 2)\%$ for all eX events [and $(90 \pm 1)\%$ for XX events at the ψ']. From the pulse-height information (shown by the dashed lines in Fig. 1), we determine that the final sample of 70 events contains less than 5 misidentified events. We conclude that the anomalous two-prong electron events occur below charm threshold.

In addition, above charm threshold, we have observed multiprong electron events ($e^{\pm} + \geq 2$ charged particles, denoted MP_e) which are dominated by charmed-particle decays.[5] If eX events also come from decays of charmed particles then the MP_e and eX cross sections should have the same energy dependence. However, we find[5,8] sharp dips in the MP_e cross sections at $E_{c.m.} = 3.85$ and 4.25 GeV in clear disagreement with the eX data. Finally, we expect the largest charmed contribution at the $\psi''(3770)$, and the data (Figs. 2 and 3) show this to be small.

The data of Fig. 2 are well fitted by the theoretical cross section for pair production of a spin-$\frac{1}{2}$ τ lepton and give a value for the τ mass of 1782^{+2}_{-7} MeV. The abrupt threshold observed between $E_{c.m.} = 3.52$ and 3.57 GeV (Fig. 3) argues against the assignment of integer spin for the τ which would result in a much more gradual threshold dependence.[9]

The decay branching ratios are determined as follows. The fit in Fig. 2(b) determines $2b_e(1 - b_e - b_{MP}) = 0.168 \pm 0.008$, where b_e is the branching ratio for $\tau \to \nu_\tau e \nu_e$ and b_{MP} is the branching ratio for $\tau \to \nu_\tau + \geqslant 3$ charged particles. The fit in Fig. 2(a) yields $2b_e b_{X,0\gamma} = 0.105 \pm 0.007$, where $b_{X,0\gamma}$ is the branching ratio for $\tau \to \nu_\tau + [1$ charged particle $(\neq e)] + $(no detected photons). Theoretically, the value of $b_{X,0\gamma}$ is expected to be dominated by three decay modes ($\mu^-\nu\nu$, $\pi^-\pi^0\nu$) and have the approximate value $(0.98 + 0.59 + 0.36 \times 1.09)b_e = 2.0b_e$.[3] The factor 0.36 indicates the probability that both photons in the π^0 decay escape detection. A detailed determination of the ratio $b_{X,0\gamma}/b_e$, based on the relative τ decay rates of Ref. 3, combined with the data of Fig. 2(a) yields $b_e = 0.160 \pm 0.013$.[10] Applying this value to the result of the fit to Fig. 2(b) gives $b_{MP} = 0.32 \pm 0.05$. The values for b_e and b_{MP} are in agreement with earlier measurements.[2,4]

In conclusion, we have observed a distinct threshold at $E_{c.m.} = 3564^{+4}_{-14}$ MeV for production of events containing one electron and one oppositely charged particle of a different type. The events are unambiguously dissociated from charmed hadrons since they are observed below charm threshold and show different cross-sectional behavior above charm threshold. The energy dependence near threshold and the absolute magnitude of the cross section for these events are consistent with a spin-$\frac{1}{2}$ heavy lepton. These data, combined with previous measurements in e^+e^- annihilation, provide overwhelming positive evidence for the existence of the third charged lepton, τ.

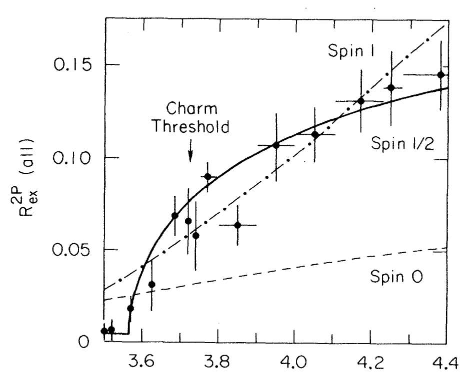

FIG. 3. R_{eX}^{2P} for all eX events with $3.50 \leqslant E_{c.m.} \leqslant 4.40$. The three fitted curves indicate the threshold behavior for different τ spins.

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[10] If the $\pi\nu$ decay mode of the τ is absent, then we measure $b_e = 0.187 \pm 0.015$.