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OBSERVATION OF A PEAK IN HADRON AND WEAK ELECTRON PRODUCTION IN e^+e^- ANNIHILATION AT $E_{c.m.} = 3770$ MeV*

W. Bacino, A. Baumgarten, L. Birkwood, C. Buchanan, R. Burns,† M. Chronoviat, P. Condon, R. Coombes, P. Cowell,‡ A. Diamant-Berger// M. Faessler,⧺ T. Ferguson, A. Hall, J. Hauptman, J. Kirkby, J. Kirz,§ J. Liu,** L. Nodulman, D. Ouimette, D. Porat, C. Rasmussen, M. Schwartz, W. Slater, H.K. Ticho, S. Wojcicki, C. Zupancic††

Stanford Linear Accelerator Center and Physics Department
Stanford University, Stanford, California 94305;

University of California, Los Angeles, California 90024;

University of California, Irvine, California 92664.

ABSTRACT

We have observed a resonance in the cross section $e^+e^- \rightarrow$ hadrons at $E_{c.m.} = 3770 \pm 6.0$ MeV of total width, $\Gamma = 24 \pm 5$ MeV and partial width to electron pairs, $\Gamma_{ee} = 180 \pm 60$ eV. The cross section of hadronic events which contain a weakly-produced electron shows a peak at the same mass and provides a lower-limit measurement of the D semileptonic branching ratio of $(9 \pm 2)\%$.

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†Current address: Hughes Aircraft, Newport Beach, California

‡Current address: Systems Control, Inc., Palo Alto, California.

//Permanent address: DPhPE, Saclay, France

⧺Current address: CERN, Geneva, Switzerland.

§Permanent address: State University of New York, Stony Brook, N.Y.

**Presently with American Asian Bank, San Francisco, California.

††Current address: Institute of Nuclear Physics, University of Munich, West Germany.

Apparatus. We report the first results of a SPEAR experiment performed with a new detector DELCO[1] (Fig. 1), designed to identify electrons over half of the total solid angle by means of a large atmospheric pressure Cerenkov counter.

Six concentric cylindrical multi-wire proportional chambers (MWPC) extend from the beam pipe to a radius of 30.0 cms. The inner four cylinders subtend 80% of 4π steradians. Azimuthal readout is provided by axial anode wires of 2mm spacing and crude depth measurement by four cylindrical HV foils divided into 1 cm wide strips inclined at $\pm 45^{\circ}$ to the beam axis.

The MWPC are in a 3.5 kG magnetic field provided by two discrete coils wrapped on steel pole pieces 85 cm apart with a return yoke on the outside of the detector. The magnet provides a near-axial field over the MWPC volume, with an average field integral out to the magnetostrictive WSC of 1.7 kG-m.

Immediately beyond the MWPC the particles enter a 12-module ethane-filled Cerenkov counter[2] sensitive only to electrons (π threshold = 3.7 GeV/c). Particles which count by striking the photocathodes are identified by plastic guard counters. Within each module, the Cerenkov light is focussed by a 1.5 × 1.5m ellipsoidal mirror via a flat mirror onto a 5" RCA 4522 phototube coated with pTP wave-shifter. The average radiator length of 1m yields 10 photo-electrons for a β=1 particle.

Next in each sextant are located 2 planes of magnetostrictive chambers providing two z and ϕ measurements per track. Together with the MWPC information they give the following measurement accuracies: $\sigma_p/p = 13p$ (GeV/c)%, $\sigma_{\phi} = 5$ mrads and $\sigma_{\theta} = 4$ mrads.

Finally there is an array of Pb/scintillator shower counters subtending 60% of 4π steradians and consisting of three layers of Pb (2 rl) and scintillator. The first layer of scintillator (A counter) is full length and is viewed at each end by a 2" phototube. The two following layers are composed of two half-length scintillators, each viewed individually.

In addition, the polar region $15^{\circ} < \theta < 35^{\circ}$ is covered by pie-shaped counters attached to the magnet pole-tips and read out via blue $\rightarrow$ green wave-length shifter bars.[3]

All of the phototube pulses are pulse height analyzed. All but those on the outer two layers of the shower counters are also time analyzed.

Trigger. There are four logical components of the trigger: the shower counters, A counters, the MWPC's, and a beam crossing pulse. A shower counter pulse (S) is defined as a coincidence of at least two of its scintillator layers, permitting relatively soft photons to satisfy S. An A pulse demands the coincidence of signals from tubes at both ends of the scintillator. A logical pulse, γ, is defined by the sum of the signals of all the tubes in the first two layers of shower counters exceeding a threshold set so as to exclude non-showering cosmic rays. A MWPC track (Q_{12}) is defined as a coincidence between two hits in the innermost pair of MWPC cylinders within approximately 3 cm. The beam crossing pulse (X) is derived from a pickup coil near the interaction region and restricts triggers to $\pm$ 20 nsec of the beam crossover time.

These components are combined to form three triggers ($C = X \cdot A \cdot 2S \cdot Q_{12}$, $H = X \cdot 2A \cdot 3S$ and $G = X \cdot \gamma \cdot 2S$), with the requirement that shower counters from separate sextants participate. The combined trigger rate is 0.7 Hz.

Event Identification. The raw data comprise typically about 8% Bhabha pairs (e^+e^-), and 5% hadronic events. The remainder are mainly cosmic rays which are removed from the sample by timing cuts (the transit time of cosmic rays is always larger than 12 nsec) and by the requirement that tracks traverse the interaction region.

The integrated luminosity is obtained from the number of detected Bhabha pairs, defined as a pair of tracks in the MWPC deviating from colinearity by no more than 10° with two associated shower counter pulses within ±3 nsec of the beam crossing pulse. Furthermore, each electron must be identified either by a shower counter pulse height ≥4 times the pulse height of a minimum ionizing particle or by a pulse in the appropriate Cerenkov cell (threshold of ~0.7 photo-electrons).

Triggers are classified as hadronic events if they satisfy all of the following:

a) At least two shower counter pulses within ± 3nsec of the beam-crossing pulse.

b) At least two visible tracks in the MWPC.

c) Vertex near the beam-crossing point, i.e., within ±10cm along the beam axis and ±1 cm perpendicular to the beam axis.

Two track events must satisfy additional criteria:

a) The two tracks are not both identified as $e^{\pm}$ by Cerenkov and shower counter pulse height.

b) The tracks are not coplanar with the beam ($\Delta\phi > 5^{\circ}$).

Candidates for hadronic events with an $e^{\pm}$ form that subset of these events in which one of the tracks traverses a Cerenkov cell and a shower counter and both of these give an in-time pulse. To reduce the background from Dalitz pairs, γ conversions and δ rays, events are not accepted into this sample if the $e^{\pm}$ track is accompanied by another track within $\Delta\phi = 15/P$ (GeV) mrads, where P is the momentum of the softer track. This cut has been measured to remove (15±5)%

of real events. The graphical reconstruction of these events is inspected by physicists in order to eliminate spurious candidates. Approximately 80% of the initial $e^{\pm}$ hadronic sample pass this final test.

Detection Efficiency. The detection efficiency of Bhabha pairs is easily understood since the topology is simple, radiative losses calculable, and the probability of identifying high-energy electrons inside the fiducial volume excellent (>99%).

The detection efficiency for hadronic events is calculated by first unfolding the "true" charged track and photon multiplicity distribution from the observed one, on the assumption of no correlation between the final state products. Once this is known, the overall trigger efficiency is readily obtained by appropriately weighing different final state efficiencies. For events with at least 4 prongs it is above 90%; and for 2 prong events it is (48±15)%. The overall triggering efficiency at $E_{c.m.}$ of 3.8 GeV is 0.85±0.1 where the error was determined by taking extreme input assumptions compatible with the data. The number of genuine events lost due to misidentification is less than 3% and is comparable to the numbe: of spurious events misidentified as hadrons.

The number of observed hadronic events with electrons has to be corrected for electron losses in the Cerenkov counter due to mirror edges and poor light collection at low momenta. We have measured these inefficiencies with Bhabha events and soft electron pairs from the process $e^+e^- \rightarrow e^+e^- \quad e^+e^-$. These losses amount to 20% when integrated over the observed electron distributions. In addition a small correction is necessary due to absorption of soft electrons in the first Pb layer of the shower counters. This was determined from test beam data and reaches 15% at 200 MeV.

Results. The measured value of R in the range 3.7 GeV $<E_{c.m.}<$ 3.83 GeV is displayed in Fig. 2a). The errors shown are statistical and the vertical scale may possess an overall systematic error of ±20%. A significant structure is observed[4] at 3.77 GeV. Fig. 2b) shows the data after removal of the ψ and ψ' radiative tails[5] (indicated in Fig. 2a). Since this peak occurs close to D^0 and D^+ thresholds we tried several Breit-Wigner fits with and without dependencies on their respective momenta, P_0 and P_+.[6] These forms included a resonant S wave or P wave with energy dependent width superposed on a background term which was either linear or proportional to $(P_0^3 + P_+^3)$. All of these give resonance parameters which agree within the errors of the fits. Specifically, a P wave final state with $(P_0^3 + P_+^3)$ background gave: mass, m = (3770 ± 6) MeV (allowing for the energy calibration of SPEAR), Γ = (24 ± 5) MeV, Γ_{ee} = (180 ± 60) eV. The error in Γ_{ee} includes ± 40 eV due to the fit and ± 40 eV due to normalization uncertainties. Our values of m and Γ agree with those of Rapidis et al.[4] while our value of Γ_{ee} is less than theirs by a factor of two. Most of the discrepancy (a factor of 1.5) is accounted for by a difference in the raw data; an additional 20% is caused by uncertainties in normalization.

The cross section of hadron events with an $e^{\pm}$ and at least two additional prongs is shown in Fig. 2c). The dot-dash line is an estimate of the background based on the assumption that there is no anaomalous electron production at the ψ or ψ' and derived from the measured probability of observing an electron per hadronic event of $(3.5\pm0.3)10^{-3}$ at the ψ and $(8.8\pm1.0)10^{-3}$ at the ψ'.[7] The dashed line shows a P-wave Breit-Wigner fit of the same mass and width as previously determined from the total hadronic cross section.

We interpret this resonance as the $^3D_1$ state of charmonium with $J^{PC} = 1^{--}$ predicted by Eichten _et al._[8] at this mass. The large width in comparison with the ψ' indicates that the new state decays almost entirely to $D^0\bar{D}^0$ and D^+D^-, leading to the interpretation of Fig. 2c) as observation of D semileptonic decays. Assuming equal semileptonic branching ratios for charged and neutral D's, the relative size of the peaks in Figs. 2b) and 2c) gives a branching ratio of $(9\pm2)\%$ for $D \to e\nu X$ where X represents any hadronic state with the requirement that the final state contains at least 3 visible charged tracks. Thus this is a lower limit on the total semileptonic rate since decays with only two visible prongs in the final state have been excluded. This branching ratio measurement is consistent with those reported[9] by other e^+e^- experiments.

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FIGURE CAPTIONS

1. Polar (a) and azimuthal (b) projections of the apparatus. For illustrative purposes, in (a) the apparatus in the yoke has been rotated by 30^{o}.

2. a) R as a function of energy, b) R after subtraction of the radiative tails of ψ and ψ'. c) Plot of R_e, defined as the ratio of the cross section for hadronic events with an electron to the point cross section. The curves are described in the text.

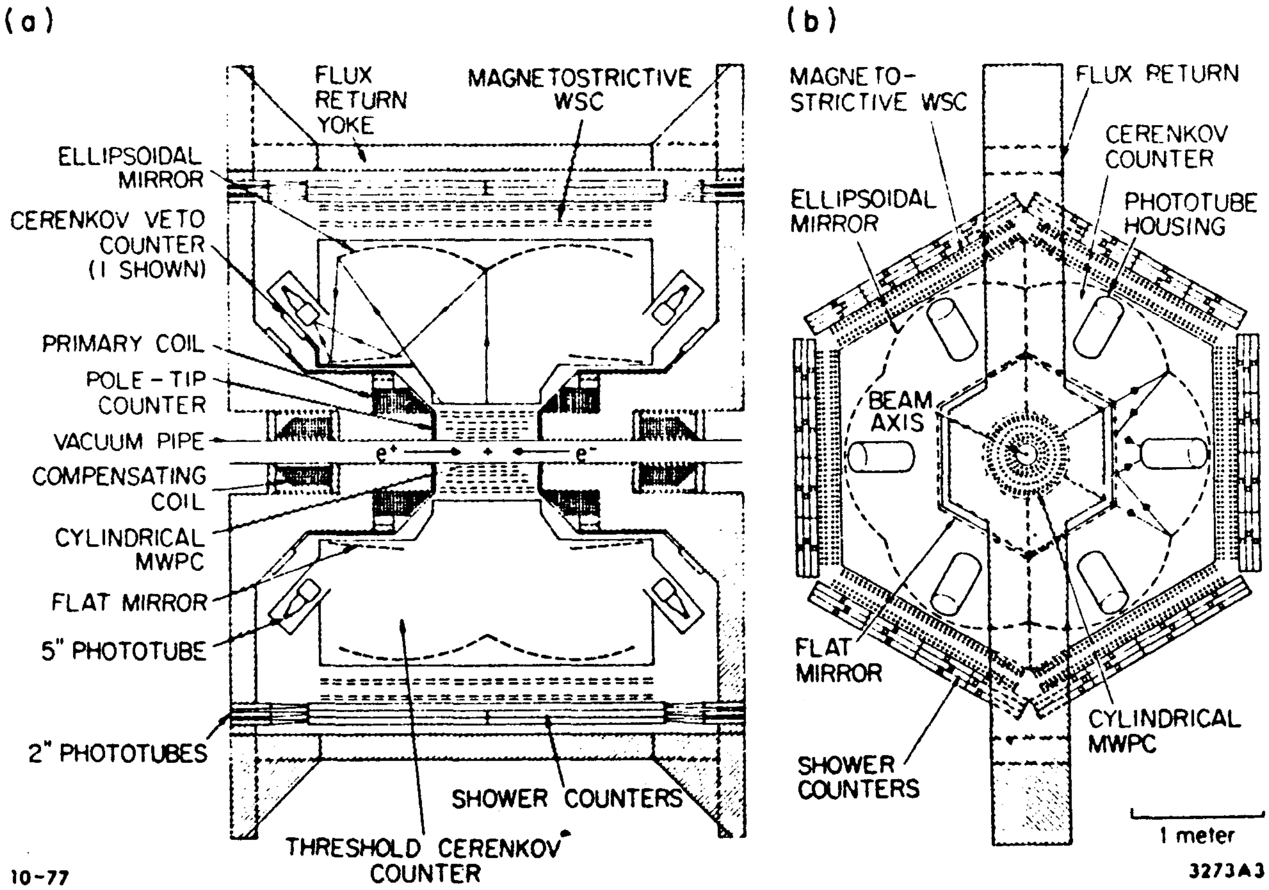
(a)
FLUX RETURN YOKE
MAGNETOSTRICTIVE WSC
ELLIPSOIDAL MIRROR
CERENKOV VETO COUNTER (1 SHOWN)
PRIMARY COIL
POLE - TIP COUNTER
VACUUM PIPE
COMPENSATING COIL
CYLINDRICAL MWPC
FLAT MIRROR
5" PHOTOTUBE
2" PHOTOTUBES
SHOWER COUNTERS
THRESHOLD CERENKOV COUNTER
e+
e-
10-77
(b)
MAGNETO-STRICTIVE WSC
FLUX RETURN
CERENKOV COUNTER
ELLIPSOIDAL MIRROR
PHOTOTUBE HOUSING
BEAM AXIS
FLAT MIRROR
CYLINDRICAL MWPC
SHOWER COUNTERS
1 meter
3273A3

Fig. 1

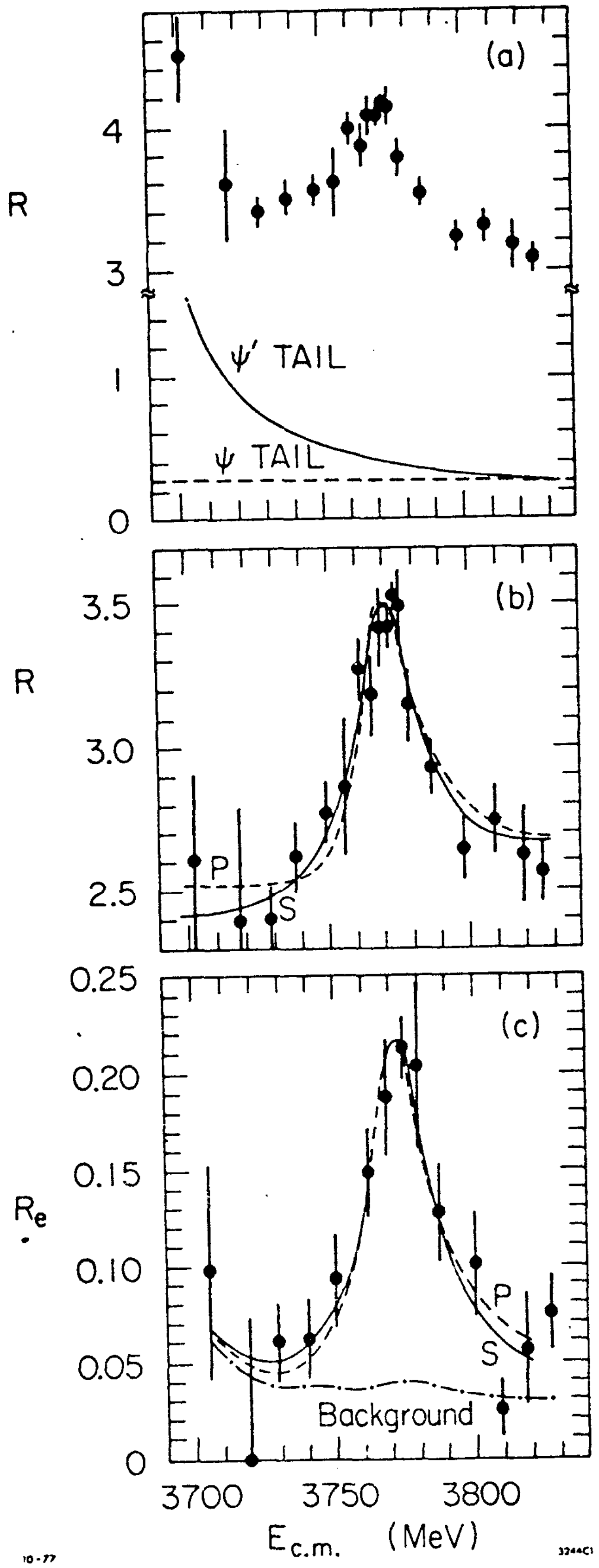
(a)
R
4
3
1
0
ψ' TAIL
ψ TAIL
(b)
R
3.5
3.0
2.5
P
S
(c)
R_e
0.25
0.20
0.15
0.10
0.05
0
P
S
Background
3700
3750
3800
$E_{c.m.}$ (MeV)
10-77
3244C1

Fig. 2