Electron-Muon and Electron-Hadron Production in e^+e^- Collisions

A. Barbaro-Galtieri, B. P. Kwan, A. M. Litke, J. M. Dorfan, R. Ely, G. J. Feldman, J. M. Feller, A. Fong, B. Gobbi, G. Hanson, J. A. Jaros, P. Lecomte, D. Lüke, R. J. Madaras, J. F. Martin T. S. Mast, D. H. Miller, S. I. Parker, M. L. Perl, I. Peruzzi,[a] M. Piccolo,[a] T. P. Pun, P. A. Rapidis, M. T. Ronan, R. R. Ross, B. Sadoulet, T. G. Trippe, V. Vuillemin, and D. E. Yount

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60201, and Stanford Linear Accelerator Center and Department of Physics, Stanford University, Stanford, California 94305, and Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

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We observe anomalous $e\mu$ and e-hadron events in e^+e^- collisions at SPEAR in an experiment that uses a lead-glass counter system to identify electrons. The anomalous events are observed in the two-charged-prong topology. Their properties are consistent with the production of a pair of heavy leptons in the reaction $e^+e^- \to \tau^+\tau^-$ with subsequent decays of $\tau^\pm$ into leptons and hadrons. Under the assumption that they come only from this source, we measure the branching ratios $B(\tau \to e\nu_e\nu_\tau) = (22.4 \pm 5.5)\%$ and $B(\tau \to h + \text{neutrals}) = (45 \pm 19)\%$.

We have observed anomalous electron production in events of the type $e^+e^- \to e^\pm x^\mp$ with or without γ rays associated with the event, where x is identified as being a muon or hadron. These data, obtained with a lead-glass electron identification system, confirm previous observations of anomalous lepton production at SPEAR[1-5] and recent observations at DESY.[6,7] This is the first report in the literature of anomalous two-prong electron-hadron (eh) events.

This experiment was performed using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-LBL) magnetic detector[8] with improved electron identification for part of the solid angle. A schematic of the apparatus is shown in Fig. 1. One octant of the magnet return yoke has been replaced by two layers of lead-glass counters interspersed with magnetostrictive spark chambers. The shower counters in that octant have been replaced by 1.9-cm-thick scintillation counters. The lead-glass system (LGW) consists of (a) a 2×26 array of lead-glass active converters, 3.3 radiation lengths (r.l.) thick, of dimensions 10.0 cm$\times$10.8 cm$\times$90 cm, and (b) a 14×19 array of lead-glass blocks, 10.5 r.l. thick, of dimensions 15 cm$\times$15 cm$\times$32 cm. This new electron and photon detector covers polar angles $60° < \theta < 120°$ and azimuthal angles $-20° < \varphi < 20°$. The lead-glass system is placed behind the 1-r.l. aluminum coil of the magnet. The presence of the magnet coil degrades the energy resolution from $\sigma/E = 5\%/E^{1/2}$ to $9\%/E^{1/2}$ (E in GeV). The absolute energy calibration[9] of the 318 lead-glass counters is done using electrons of known energy provided by Bhabha scattering.

The electrons are identified by measuring separately E_1, the energy deposited in the first 3.3 r.l. of the lead-glass system, and E_2, the energy deposited in the subsequent 10.5 r.l. of lead-glass. We also measure the momenta p of the electrons using the tracking chambers of the magnetic detector. We use electrons from quantum electrodynamic (QED) processes to study the electron signal in the LGW. Assuming that there are no

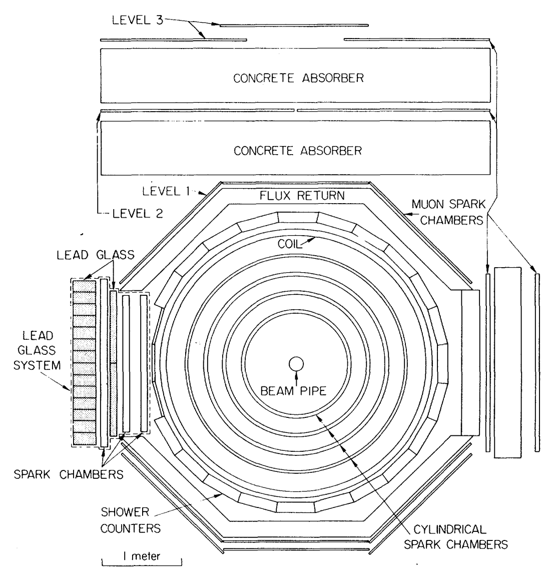

FIG. 1. Magnetic detector as seen looking along the incident beams. The porportional chambers around the beam pipe and the trigger counters are not shown. The lead-glass system (LGW) is shown on the left of the figure. Details on this addition are given in the text.

anomalous electrons produced at the $\psi(3095)$, we use hadronic decays of the ψ to determine the behavior of hadrons in the LGW and to calculate the hadron background in the electron sample. By studying scatter plots of E_1 vs E_T/p (where $E_T = E_1 + E_2$) for QED electrons and for hadrons at the ψ, we have chosen the following criteria for electron identification: (a) $E_1 > 0.150$ GeV to exclude noninteracting particles, (b) $E_T/p > 0.65$. With these criteria the average hadron contamination is $P_{h\to e} = (2.0 \pm 0.5)\%$, where $P_{h\to e}$ indicates the probability that a hadron is identified as an electron. The average efficiency for electron detection is $\epsilon = 0.89 \pm 0.07$. Our low-momentum electron identification cutoff is at 400 MeV/c for this analysis.

The momentum analysis and particle identification system of the SLAC-LBL magnetic detector is the same as described in Refs. 1 and 8. The charged particles outside the LGW are identified as muons, hadrons, or electrons in the lead-scintillator shower counters and in the magnetostrictive spark chambers following the 20-cm-thick iron flux return of the magnet. This system allows separation among muons, hadrons, and electrons for $p > 0.65$ GeV/c. The misidentification among various types of particles in the magnetic detector has been determined using the ψ data and events with five or more charged prongs at the other energies. The various probabilities averaged over the observed momentum spectrum of the particles outside the LGW are $P_{e\to h} = 0.095 \pm 0.020$, $P_{e\to\mu} = 0.01 \pm 0.01$, $P_{\mu\to h} = 0.03 \pm 0.01$, and $P_{h\to\mu} = 0.18 \pm 0.01$.

We report here results from data taken in three different energy ranges: (a) $s^{1/2} = 4.1$–4.2 GeV, (b) $s^{1/2} = 4.4$–5.8 GeV, and (c) $s^{1/2} = 6.4$–7.4 GeV. The overall integrated luminosity is 8.6 pb^{-1}, about 60% of it in interval (c). The sample includes 26 200 two-prong events, the great majority of which are QED events of the type $e^+e^- \to e^+e^-$, $e^+e^-\gamma$, $\mu^+\mu^-$, $\mu^+\mu^-\gamma$ and events of the type $e^+e^- \to e^+e^-e^+e^-$, $e^+e^-\mu^+\mu^-$, where the first two electrons escape along the beam direction. In order to reduce backgrounds from these sources we require that (1) the two prongs to be acoplanar about the incident beams by at least 20° ($\theta_{cop} > 20°$) and (2) the square of the missing mass recoiling against the two prongs to be $M_m^2 > M_0^2$, with $M_0^2 = 0.8$ GeV^2, 1.1 GeV^2, 1.5 GeV^2 for $s^{1/2}$ intervals (a), (b), (c), respectively. These criteria, along with the already mentioned cuts on $p_e > 0.4$ GeV/c, $p_x > 0.65$ GeV/c, leave the events shown in Table I, where the first particle is identified in the LGW, the second in the magnetic detector,[10] and the γ is detected in any part of the apparatus. Using the misidentification probabilities quoted earlier, we can calculate the background expected in the $e\mu$ and the eh events from the ee and the hh events. We obtain the backgrounds shown in Table I. After background subtraction, we correct the events for the probability that each particle is properly identified in the main detector ($\epsilon_e = 0.89 \pm 0.02$, $\epsilon_h = 0.58 \pm 0.05$, and $\epsilon_\mu = 0.94 \pm 0.02$) and use the misidentification probabilities $P_{\mu\to h}$ and $P_{h\to\mu}$ to obtain the true number of $e\mu$ and eh events from the observed ones. The corrected numbers are shown in the last two columns of Table I.[11] In summary, of the 21 $e\mu$ events observed, only 0.4 events can be attributed to background from conventional sources and of the 31 eh and $eh\gamma$, only 12.1 are background. The remainder we believe to be due to a nonconventional process.[12]

TABLE I. Observed and corrected charge-zero two-prong events with $\theta_{cop} > 20°$ and $M_m^2 > M_0^2$, where M_0^2 is defined in the text for the three different energy intervals. The momenta of the two particles are $p_1 > 0.4$ GeV/c and $p_2 > 0.65$ GeV/c. The first particle is always detected in the LGW. N_γ is the detected number of γ rays associated with the events. Here a hadron in the LGW is any particle not identified as electron. The backgrounds to the anomalous events from ee and hh are shown in columns 3 and 4. The last two columns show the true number of events after corrections due to $P_{h\to\mu}$ and $P_{\mu\to h}$ and corrections for efficiencies.

	Observed events		Background		Corrected events	
	$N_\gamma = 0$	$N_\gamma > 0$	$N_\gamma = 0$	$N_\gamma > 0$	$N_\gamma = 0$	$N_\gamma > 0$
$e\mu$	21	8	0.4	1.4	21.6 ± 6.4	3.7 ± 4.5
eh	12	19	3.0	9.1	20.5 ± 9.6	24.2 ± 12.9
ee	23	71			32.1 ± 6.9	100 ± 14
hh	38	122			66 ± 13	213 ± 30

TABLE II. Observed branching ratios for the heavy-lepton decays $\tau \to e\nu_e\nu_\tau$ and $\tau \to$ (hadrons + neutrals) deduced from the production and decay sequence of Reactions (1)–(4). For the hadronic branching ratio, *eh* events with and without γ rays were included. The branching ratios have been calculated assuming $B_e = B_\mu$, the $V-A$ coupling, and point-production cross section for a τ of mass $M = 1.9$ GeV and $M_{\nu_\tau} = 0$. Only statistical errors are shown. For systematic errors, see text.

$s^{1/2}$ (GeV)	Branching ratio for $\tau \to e\nu_e\nu_\tau$ (%)	Branching ratio for $\tau \to h$ + neutrals (%)
4.1–4.2	21.3 ± 8.5	37 ± 43
4.4–5.8	20.4 ± 5.4	50 ± 29
6.4–7.4	24.1 ± 4.6	45 ± 26
Average	22.4 ± 3.2	45 ± 17

Previous observations of anomalous two-prong lepton production[1-7] have been interpreted as being due to production and decay of a heavy lepton. We will now accept this as a working hypothesis and show that the anomalous electron signal observed in this experiment is consistent with being due to the following processes:

$$e^+e^- \to \tau^+\tau^-, \qquad (1)$$

$$\tau^\pm \to e^\pm \nu_e \nu_\tau, \qquad (2)$$

$$\tau^\mp \to \mu^\mp \nu_\mu \nu_\tau, \qquad (3)$$

$$\tau^\mp \to h^\mp + \text{neutrals}, \qquad (4)$$

where $\tau^\pm$ is a lepton[4] with $M_\tau = 1.9$ GeV and $h^\mp$ indicates a hadron (π or K). In these calculations we have ignored a possible contribution to the anomalous electron signal from semileptonic decays of charmed particles. We are presently investigating this assumption; meanwhile the measured branching ratios should be considered as upper limits.

(1) *Branching ratios.*—In order to calculate branching ratios B_e and B_h for the above decays, we write $\sigma(e\mu) = 2A_{e\mu}\sigma(e^+e^- \to \tau^+\tau^-)B_eB_\mu$ and $\sigma(eh) = 2A_{eh}\sigma(e^+e^- \to \tau^+\tau^-)B_eB_h$, where $A_{e\mu}$ and A_{eh} are the acceptances of the apparatus for $e\mu$ and eh events, respectively. We take σ to be the pointlike cross section for production of a pair of charged leptons of mass 1.9 GeV; $\sigma = (43.4/s)\beta \times (3-\beta^2)$ nb, $\beta = v_\tau/c$. For the purpose of calculating the acceptances, we assume $V-A$ coupling, and $M_{\nu_\tau} = 0$. In calculating A_{eh} we further assume that only the decays $\tau^\pm \to \pi^\pm\nu_\tau$ and $\tau^\pm \to \rho^\pm\nu_\tau$ contribute to two-prong *eh* events. We expect these two channels to constitute 73% of the hadronic decays.[13]

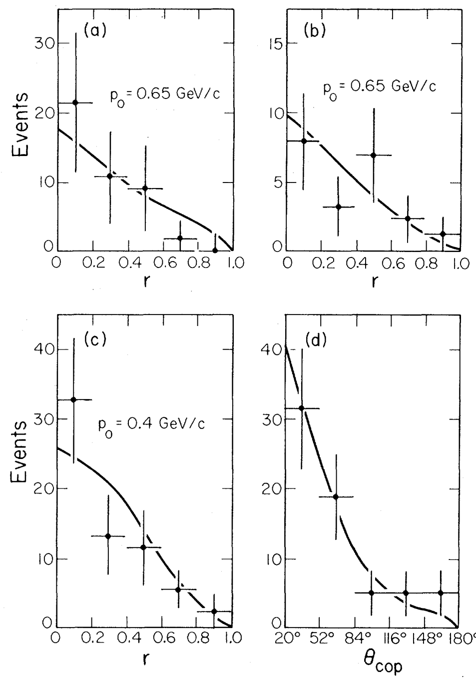

FIG. 2. The $r = (p-p_0)/(p_{max}-p_0)$ distributions for (a) the hadrons of the anomalous events, (b) the muons of the anomalous $e\mu$, and (c) the electrons of the anomalous eh and $e\mu$. (d) Coplanarity distribution for all the anomalous electron events. The curves shown are the predictions for heavy leptons of Reactions (1)–(4), with $M_\tau = 1.9$ GeV, $M_{\nu_\tau} = 0$, $V-A$ coupling, and the point-production cross section, $\sigma = (43.4/s)\beta(3-\beta^2)$ nb. In these plots the three energy regions have been combined. The hadron curve has been calculated with the assumptions explained in the text.

We compute B_e using only the $e\mu$ events and assuming $B_e = B_\mu$. We then use this value of B_e to compute B_h from the number of *eh* events. The results are shown in Table II. The three values of the branching ratios are in good agreement, showing that the observed effect has the expected energy dependence. By combining the data and including an estimated 20% systematic error, we obtain $B_e = (22.4 \pm 5.5)\%$ and $B_h = (45 \pm 19)\%$, in good agreement with the theoretical values for the τ, $B_e = 20\%$ and $B_h = 45\%$.[13]

(2) *Momentum distributions.*—Figures 2(a)–2(c) show the corrected event distribution of the variable r for the hadrons, the muons, and the electrons of the anomalous events. The variable r is defined as $r = (p - p_0)/(p_{max} - p_0)$, where p_0 is the low-momentum cutoff ($p_0 = 0.4$ GeV/c for electrons and 0.65 GeV/c for muons and hadrons) and

p_{max} is the maximum momentum allowed for the heavy-lepton hypothesis. Figure 2(d) shows the corrected coplanarity-angle distribution for all the anomalous events. The curves shown have been calculated with the same assumptions used for the branching-ratio calculations and are normalized to the number of events in each plot. The first bin of the r distribution in Fig. 2(c) is higher than the heavy-lepton prediction, which may indicate some contamination from decays of charmed particles.

In summary, with good electron identification we have observed anomalous electron production which is consistent with that expected from production and decay of a pair of heavy leptons. Assuming no charm contamination, we have measured the branching ratio $B_e = (22.4 \pm 5.5)\%$, which is consistent with theoretical expectation[13] and with previously reported measurements.[14] We have also observed for the first time anomalous electron-hadron events that give $B_h = (45 \pm 19)\%$.

We are indebted to the people who have built the Mark I detector and prepared the facility software, but have not participated in this experiment. We also thank the LBL and SLAC technicians who were instrumental in setting up the lead-glass system, and we thank Barrie Pardoe for his invaluable contribution to the software.

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(a)Permanent address: Laboratori Nazionali di Frascati dell'INFN, Frascati (Rome), Italy.

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[10]There are two out of the 52 anomalous events in Table I that have both the electron and the other particle in the LGW. For these two events the second particle was identified as a hadron because it interacted in the active converter.

[11]The number of charge ± 2 events with an identified electron are $N(e\mu) = 0$, $N(e\mu\gamma) = 0$, $N(eh) = 1$, $N(eh\gamma) = 3$. Also, there are one ee, 25 hh, and 57 $hh\gamma$ events. After we perform the same calculations as for the charge-zero events, we find the electron candidates to be consistent with background.

[12]For $e\mu$ events reported in Refs. 1 and 2, a number of hypotheses on the missing particles have been tested and excluded (see Ref. 4). We do not discuss those tests here.

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[14]These values are $B_e = (18.6 \pm 3.0)\%$ reported in Refs. 1 and 4; $B_\mu = (17.5 \pm 4.0)\%$ in Refs. 3 and 4; $B_e = (14 \pm 4)\%$ and $B_\mu = (15 \pm 3)\%$ in Ref. 6.