

**PROPERTIES OF ANOMALOUS  $e\mu$   
EVENTS PRODUCED IN  $e^+e^-$  ANNIHILATION<sup>☆</sup>**

M.L. PERL, G.J. FELDMAN, G.S. ABRAMS, M.S. ALAM, A.M. BOYARSKI, M. BREIDENBACH,  
F. BULOS, W. CHINOWSKY, J. DORFAN, C.E. FRIEDBERG, G. GOLDBERGER<sup>1</sup>, G. HANSON,  
F.B. HEILE, J.A. JAROS, J.A. KADYK, R.R. LARSEN, A.M. LITKE, D. LÜKE<sup>2</sup>, B.A. LULU,  
V. LÜTH, R.J. MADARAS, C.C. MOREHOUSE<sup>3</sup>, H.K. NGUYEN<sup>4</sup>, J.M. PATERSON,  
I. PERUZZI<sup>5</sup>, M. PICCOLO<sup>5</sup>, F.M. PIERRE<sup>6</sup>, T.P. PUN, P. RAPIDIS, B. RICHTER,  
B. SADOULET, R.F. SCHWITTERS, W. TANENBAUM, G.H. TRILLING, F. VANNUCCI<sup>7</sup>,  
J.S. WHITAKER and J.E. WISS

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA  
and Lawrence Berkeley Laboratory and Department of Physics,  
University of California, Berkeley, California 94720, USA*

Received 15 July 1976

We present the properties of 105 events of the form  $e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{missing energy}$ , in which no other charged particles or photons are detected. The simplest hypothesis compatible with all the data is that these events come from the production of a pair of heavy leptons, the mass of the lepton being in the range 1.6 to 2.0 GeV/c<sup>2</sup>

In a previous letter [1] we reported the observation of 64 events of the form

$$e^+e^- \rightarrow e^\pm\mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we could find no conventional explanation. Through the acquisition of additional data we now have 105 examples of this reaction (after the subtraction of 34 background events). We have studied the properties of these events and have deduced: a) that they are consistent with the production and decay of a pair of new particles

$$e^+ + e^- \rightarrow U^+ + U^-, \quad (2)$$

<sup>\*</sup> Work supported by the Energy Research and Development Administration.

<sup>1</sup> Miller Institute for Basic Research in Science, Berkeley, California, USA.

<sup>2</sup> Fellow of Deutsche Forschungsgemeinschaft.

<sup>3</sup> Permanent address: Varian Associates, Palo Alto, California, USA.

<sup>4</sup> Permanent address: LPNHE, Université Paris VI, Paris, France.

<sup>5</sup> Permanent address: Laboratori Nazionali, Frascati, Rome, Italy.

<sup>6</sup> Permanent address: Centre d'Etudes Nucléaires de Saclay, France.

<sup>7</sup> Permanent address: Institut de Physique Nucléaire, Orsay, France.

the  $e$  and  $\mu$  in reaction (1) being the decay products of the  $U$ 's; b) that each new particle,  $U$ , decays to a charged lepton and at least two undetected particles; and c) that for most of the events the undetected particles are consistent only with being neutrinos.

The events reported were found using the SLAC-LBL magnetic detector at SPEAR. The event selection criteria and background calculations are given in detail in refs. [1-3]. Briefly, we require two and only two oppositely charged prongs in the detector. They both are required to have momenta over 650 MeV/c to permit  $e$  and  $\mu$  identification. One must be identified as an  $e$  and the other as a  $\mu$  by the detector and no photons may be detected. Finally, to reduce contamination from  $e^+e^-$  and  $\mu^+\mu^-$  pair production, the two prongs must be acoplanar with the incident beams by more than 20°.

The observed cross section for these events, uncorrected for momentum and geometrical cuts, is shown in fig. 1 as a function of center of mass energy  $E_{\text{cm}}$ . Cross section curves for a sequential heavy lepton [4-6] of masses 1.6 and 1.8 GeV/c<sup>2</sup> with leptonic decay modes

$$U^- \rightarrow \nu_U + e^- + \bar{\nu}_e, \quad U^- \rightarrow \nu_U + \mu^- + \bar{\nu}_\mu; \quad (3)$$

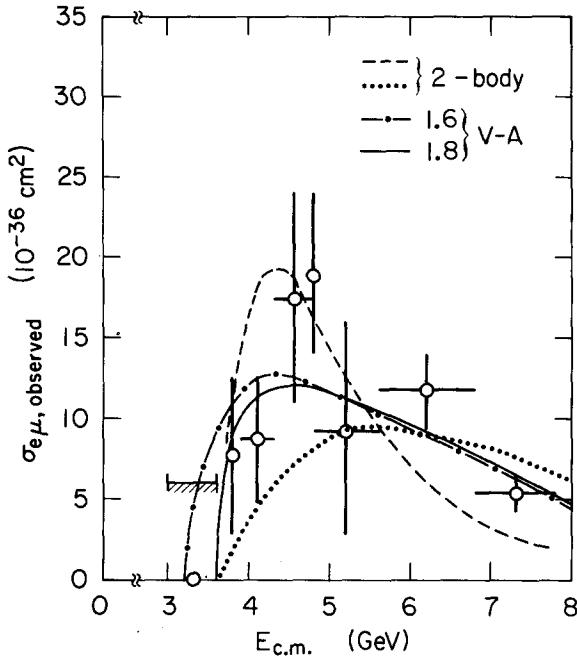


Fig. 1. The observed  $e\mu$  production cross section, corrected for background. The horizontal bars indicate the  $E_{cm}$  region covered by the data point. There are no  $e\mu$  events before background subtraction in the 3.0–3.6 GeV region; the cross hatched lines is a 90% confidence upper limit. The curves are theoretical U particle pair production cross sections corrected for geometric acceptance, angular cuts, and momentum cuts. These cross section curves are fit to  $\sigma_{e\mu}$ , observed as follows: The solid and dash-dot curves are for heavy leptons, reaction (3), of mass 1.8 and 1.6  $\text{GeV}/c^2$  respectively,  $M_{\nu U} = 0.0$ , V – A coupling and the point production cross section  $\sigma_{ee \rightarrow U\bar{U}} = 43.4 \beta(3 - \beta^2)/s \text{ nb}$ . The dotted and dashed curves are for a boson of mass 1.8  $\text{GeV}/c^2$  with the 2-body decay modes of reaction (4), a production cross section  $\sigma_{ee \rightarrow U\bar{U}} = \eta\beta^3 |F_U(s)|^2/s$  where  $\eta$  is a constant and  $F_U(s)$  is a production form factor. For the dotted and dashed curves  $F_U(s) = \text{constant}$  and  $F_U(s) = \text{constant}/s$  respectively. All spin-spin correlations and polarization effects are ignored.

and for a vector meson<sup>†1</sup> of mass 1.8  $\text{GeV}/c^2$  with the 2-body leptonic decay modes

$$U^- \rightarrow e^- + \bar{\nu}_e, \quad U^- \rightarrow \mu^- + \bar{\nu}_\mu \quad (4)$$

are also shown.

As discussed in ref. [8], the curves show that the threshold for U particle production depends primarily on the mass,  $M_U$ , of the U and only weakly on the production or decay hypothesis.

<sup>†1</sup> The most popular model for such a meson is provided by the charm theories [7].

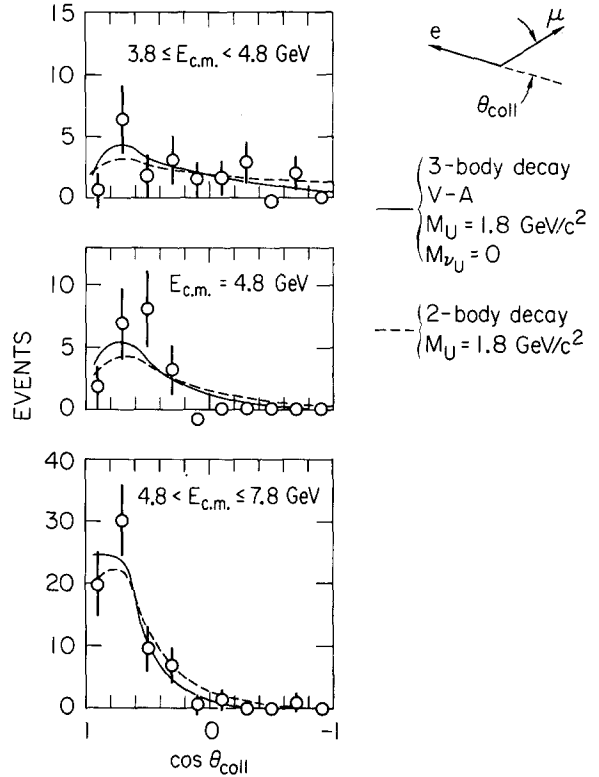
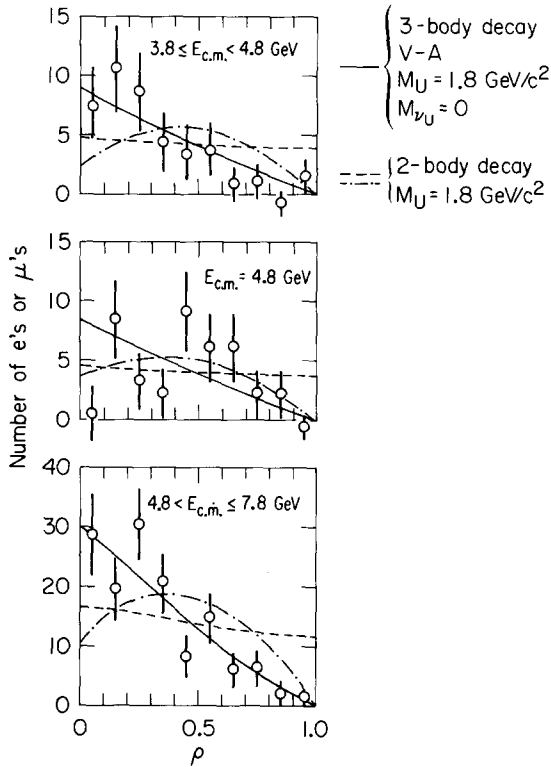


Fig. 2. The  $\cos \theta_{coll}$  distributions. The solid curves are for a heavy lepton with  $M_U = 1.8 \text{ GeV}/c^2$ ,  $M_{\nu U} = 0.0$ , and V – A coupling. The dashed curves are for a boson with the 2-body decay modes of reaction (4) and  $M_U = 1.8 \text{ GeV}/c^2$ . The curves are normalized to the total number of events. All spin-spin correlations and polarization effects are ignored. The data are corrected for background contamination.

Evidence that the origin of these events is the decay of a pair of new particles is obtained from the distribution of the angles between the two prongs. Fig. 2 shows the distribution of the cosine of the collinearity angle,  $\cos \theta_{coll} = -\mathbf{p}_e \cdot \mathbf{p}_\mu / (|\mathbf{p}_e| |\mathbf{p}_\mu|)$ , for three  $E_{cm}$  regions. At low energy the angles are much more uncorrelated than at high energy. This is characteristic of the decay of a pair of fixed mass particles; as the energy increases, the Lorentz transformation forces the decay products back to back. The data in fig. 2 have been corrected for background events, which do not exhibit this behavior. As illustrated, the predicted  $\cos \theta_{coll}$  distributions are shown in fig. 2 for reactions (3) and (4).

These data, figs. 1 and 2, indicate that the mass of



the new particle is probably in the range 1.6 to 2.0 GeV/c<sup>2</sup>. A detailed determination of the mass will be presented elsewhere.

Evidence that each new particle decays into at least three bodies is obtained from a study of the inclusive momentum spectrum. To combine data from different energies we construct a parameter  $\rho$ ,

$$\rho = \frac{p - 0.65}{p_{\max} - 0.65},$$

where  $p$  is the momentum of each detected particle in GeV/c and  $p_{\max}$  is the maximum momentum allowed for the decay of a 1.8 GeV/c<sup>2</sup> particle into massless particles. (The use of any mass in the range 1.6 to 2.0 GeV/c<sup>2</sup> would not alter our conclusions.) The  $\rho$  distributions are given in fig. 3 for three energy ranges. Background contamination has been subtracted. The background  $\rho$  distributions are similar to the signal  $\rho$  distributions; thus, the background subtraction does not appreciably alter the distributions.

In fig. 3 the solid curve is for a heavy lepton, reaction (3), with  $M_U = 1.8 \text{ GeV}/c^2$ ,  $M_{\nu_U} = 0.0$  and V - A coupling; and the dashed curve is for a mass 1.8 GeV/c<sup>2</sup> boson with the 2-body decay modes of reaction (4) ignoring spin correlations or polarization effects. The dot-dashed curve represents an extreme case of polarization of a 1.8 GeV/c<sup>2</sup> vector meson with 2-body decay modes, reaction (4); the mesons being only in the helicity = 0 states<sup>#2</sup>. Values of  $\chi^2$  for these hypotheses are shown in table 1 for the three energy ranges. The

<sup>#2</sup> Putting the vector meson only in the helicity = 0 state is an approximation to what happens if the meson has a large anomalous magnetic moment [9].

Fig. 3. The distribution in  $\rho = (p - 0.65)/(p_{\max} - 0.65)$  where  $p$  is the momentum of the e or  $\mu$  in GeV/c, corrected for background contamination. For the meaning of the solid and dashed curves see the caption of fig. 2. The dot-dashed curves is for the 2-body decay mode of a pair of 1.8 GeV/c<sup>2</sup> vector mesons each polarized completely in the helicity = 0 state.

Table 1  
 $\chi^2$  tests of  $\rho$  distributions.  $E_{\text{cm}}$  in GeV.

	$3.8 \leq E_{\text{cm}} < 4.8$	$E_{\text{cm}} = 4.8$	$4.8 < E_{\text{cm}} \leq 7.8$	$3.8 \leq E_{\text{cm}} \leq 7.8$
Degrees of freedom	4	4	9	9
$\chi^2$ for heavy lepton, reaction (3), $M_U = 1.8 \text{ GeV}/c^2$ , $M_{\nu_U} = 0.0$ , V - A	2.2	9.5	8.6	4.3
$\chi^2$ for boson with 2-body decay, reaction (4), $M_U = 1.8 \text{ GeV}/c^2$ no spin correlation or polarization	28.3	10.5	98.0	107.4
$\chi^2$ for vector meson with 2-body decay, reaction (4), $M_U = 1.8 \text{ GeV}/c^2$ each meson only in helicity = 0 state	20.6	3.3	38.1	35.4

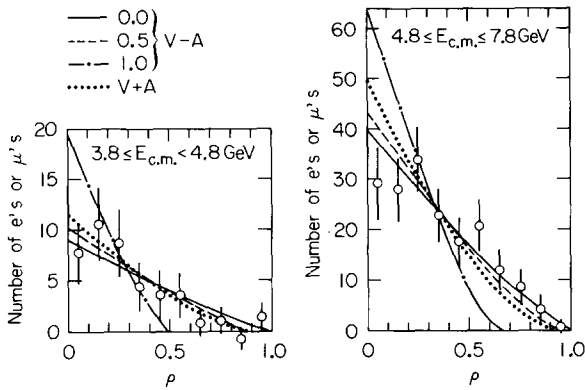


Fig. 4. Comparison of  $\rho$  distributions with: solid and dashed curves, V - A heavy lepton,  $M_U = 1.8 \text{ GeV}/c^2$ , and  $M_{\nu U}$  in  $\text{GeV}/c^2$  as indicated; dotted curve V + A heavy lepton,  $M_U = 1.8 \text{ GeV}/c^2$ , and  $M_{\nu U} = 0.0$ .

4.8 GeV data are inconclusive, but the higher and lower energy data strongly favor three body decay modes. Taking all of the data together, two body decay modes are excluded.

Evidence that the two undetected particles in each decay are neutrinos comes from systematically eliminating all other possibilities. The neutron is eliminated as a candidate for one of the undetected particles by the  $\rho$  distributions which set an upper limit of 0.7  $\text{GeV}/c^2$  (95% confidence level) on the mass which can be possessed by any of the undetected particles in the three body decay<sup>#3</sup>. Fig. 4 shows these distributions with curves representing the distributions expected for a 1.8  $\text{GeV}/c^2$  heavy lepton decaying to two massless particles and a heavy neutrino via a V - A coupling. The use of other couplings or of phase space has no effect on this conclusion since a high mass undetected particle limits the maximum value of  $\rho$  independent of the coupling.

To determine whether a  $K_L^0$  could be one of the undetected particles, we searched for events of the form  $e^+e^- \rightarrow e^+\mu^+K_S^0 + \text{missing energy}$  (5)

where the  $K_S^0$  is detected by its decay  $K_S^0 \rightarrow \pi^+\pi^-$ . In a data sample which contained 82  $e\mu$  events of reaction (1)<sup>#4</sup>, only one example of reaction (5) was ob-

<sup>#3</sup> This eliminates the possibility that the U is a charmed baryon with decays like  $U^- \rightarrow e^- + \bar{\nu}_e + n$ , or that it is a fermion of the type discussed by Goldhaber [10].

Table 2

The number of events with an identified oppositely charged electron and muon categorized by total observed charged multiplicity and by whether photons are detected. The numbers in parentheses represent minimal and maximal background estimates and are explained in the text.

Charged multiplicity	no photons	$\geq$ one photon
2	110 (14 - 28)	109 (51 - 104)
3	67 (28 - 58)	198 (94 - 193)
4	79 (37 - 76)	338 (180 - 356)
$\geq 5$	101 (56 - 109)	884 (506 - 971)

served. Assuming that the decay rate of the new particle into  $K_L^0$  is equal to the decay rate to  $K_S^0$ , the fraction of decays in reaction (1) containing a  $K^0$  is less than 0.09 at the 90% confidence level.

To determine whether the undetected particles could be photons,  $\pi^0$ 's, or charged particles which escape detection by passing through uninstrumented sections of the detector, we construct a table, table 2, of all events which contain an oppositely charged electron and muon. Events are categorized by charged multiplicity and whether photons were detected in the shower counters. The data sample is the same as was used for the  $K_S^0$  search. The e and  $\mu$  selection is similar to that used for reaction (1) except that no coplanarity requirement was imposed in events with three or more charged prongs.

Two estimates of the number of events we expect from misidentifications of hadronic events are included in table 2. The first is an estimate obtained from misidentification probabilities as a function of momentum measured in  $\psi$  decays, assuming no anomalous sources of lepton production in these decays. The second is an estimate obtained from three or more prong events in the data set from which the table is constructed. The true numbers of events caused by hadron misidentifications is probably somewhere between the two limits given in table 2 because misidentification probabilities can increase with c.m. energy.

<sup>#4</sup> The data sample is all events for which a proportional chamber around the beam pipe was operational. This chamber was used in the  $K_S^0$  identification.

Table 3

90% confidence level upper limits on the fraction of decays in reaction (1) which can contain an undetected particle or combination of particles. The smaller backgrounds given in table 2 have been used. The total is less than the sum of the limits due to the quadratic addition of errors and elimination of double counting between modes.

Undetected particle(s)	90% confidence upper limit
$K^0$	0.09
$\pi^0$ or $\gamma$	0.18
Charged particle	0.09
Charged particle + $\pi^0$ or $\gamma$	0.11
TOTAL	0.39

At the present stage of analysis, table 2 argues neither for nor against anomalous di-lepton production in topologies other than the two prong, no photon, topology. The sole function of the table is to show that there are an insufficient number of events in the other topologies to explain the events from reaction (1) as events in which additional charged particles or photons are produced, but escape detection.

For example, assume that events in reaction (1) were to be explained as events in which each new particle decayed into a lepton, a  $\pi^0$ , and a neutrino, but that neither  $\pi^0$  was detected by the shower counters. Since the typical efficiency for detecting at least one photon from a  $\pi^0$  decay is 0.65, there is only a 0.12 probability of 2  $\pi^0$ 's escaping detection. Thus, to explain the 82 anomalous two prong events without photons, we would have to observe 600 two prong events with photons. From table 2, there are only 109 events of this type, and only 58 events after the subtraction of the minimal background.

Similar arguments can be made for any combination of undetected charged and neutral particles. Table 3 gives upper limits on the fraction of decays in reaction (1) which could have undetected photons or charged particles of various types, using the minimal background estimates from table 2. Overall, using very conservative estimates of backgrounds, at the 90% confidence level only 39% of the anomalous decays can contain undetected photons or charged particles.

In conclusion, a study of the properties of anomalous  $e\mu$  events (reaction (1)), indicates that if they are

to be explained by a single hypothesis, then they must arise from the decays of a pair of new particles each of which decays to a charged lepton and two neutrinos. This new particle is thus a candidate for being a heavy lepton<sup>‡5</sup> with a mass in the range 1.6 to 2.0 GeV/c<sup>2</sup>. Using  $\sigma_{e\mu}$ , observed, fig. 1, the theoretical point production cross section, and a Monte Carlo calculation of the detection efficiency, we find for such a lepton the leptonic branching ratios.

$$\frac{\Gamma(U^- \rightarrow \nu_U e^- \bar{\nu}_e)}{\Gamma(U^- \rightarrow \text{all})} = \frac{\Gamma(U^- \rightarrow \nu_U \mu^- \bar{\nu}_\mu)}{\Gamma(U^- \rightarrow \text{all})} = 0.17^{+0.06}_{-0.03}$$

We assume equal decay rates to the e and  $\mu$  modes, V - A coupling,  $M_U = 1.8$  GeV/c<sup>2</sup>, and  $M_{\nu_U} = 0.0$ .

We are very grateful to Y.S. Tsai for his help in the theory and calculations associated with this work.

<sup>‡5</sup> For a discussion of the compatibility of the heavy lepton hypothesis with other data see ref. [8].

## References

- [1] M.L. Perl et al., Phys. Rev. Lett. 35 (1975) 1489.
- [2] M.L. Perl in Proc. Summer Institute on Particle physics (SLAC, Stanford, Calif. 1975) p. 333; also issued as SLAC-PUB-1664.
- [3] G.J. Feldman, in Proc. Intern. Symp. on Lepton and photon interactions at high energy (Stanford Univ. Stanford, 1975), p. 39.
- [4] A review as of October, 1974 on heavy lepton theories and searches is M.L. Perl and P. Rapidis, SLAC-PUB-1496 (1974) (unpublished).
- [5] Y.S. Tsai, Phys. Rev. D4 (1971) 2821.
- [6] J.D. Bjorken and C.H. Llewellyn Smith, Phys. Rev. D7 (1973) 887.
- [7] S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285; M.K. Gaillard, B.W. Lee and J.L. Rosner, Rev. Mod. Phys. 47 (1975) 277.
- [8] M.L. Perl, in Proc. 1976 Neutrino Conf. (Aachen, 1976), also issued as SLAC-PUB-1764 (1976).
- [9] G. Altarelli, N. Cabibbo and L. Maiani, Phys. Rev. Lett. 35 (1975) 635; F. Bletzacker and H.T. Nieh, SUNY at Stony Brook Preprint ITP-SB-76-32 (1976); A. Gavielides and T.K. Kuo, Physics Dept., Purdue University preprint (1976).
- [10] M. Goldhaber, Phys. Rev. Lett. 1 (1958) 1521.