A SEARCH FOR NEW HEAVY LEPTONS AT PETRA

JADE Collaboration

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Received 14 January 1983

Results are presented on a search for new heavy leptons, a sequential heavy lepton $L^{\pm}$, and an electron-type neutral heavy lepton E^0, using the JADE detector at PETRA. No evidence for either of these particles was observed. A lower mass limit for the $L^{\pm}$ is determined to be 18.0 GeV/c^2 at 95% CL. Lower mass limits for the E^0 are 24.5 GeV/c^2 and 22.5 GeV/c^2, in the case of universal V + A and V − A coupling at the W–e–E vertex, respectively.

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In this letter we report on a search for new heavy leptons, a charged lepton ($L^{\pm}$), and an electron-type neutral heavy lepton (E^0, $\overline{E^0}$) produced in e^+e^- annihilation. The experiment was performed with the JADE detector at the e^+e^- colliding machine PETRA.

Some experiments have already performed searches for the new sequential heavy lepton of a fourth generation [1–3]. Preliminary results from JADE have been reported [4] ‡1.

No direct experiment searching for a neutral heavy electron with a mass above 1.2 GeV/c^2 has been performed, except in ref. [4]. The previous lower mass limit, 1.2 GeV/c^2 was determined from the absence of the decay $\tau \to \nu_\tau E^0 e$ [5] at SPEAR [6]. In this report more systematic searches for these particles are presented.

The JADE detector has already been described elsewhere [7]. The following features are essential for the present analysis. The cylindrical drift chamber (jet chamber), which is situated in a solenoid magnetic field of 4.8 kG, covered 97% of the solid angle and measured the momenta of the outgoing charged particles. The energies of γ's and electrons were measured with lead glass shower counters, which consist of a cylindrical array of 2520 counters and arrays of 96 endcap counters at both sides. A muon filter system surrounds the lead glass counters; it consists of 4 or 5 layers of drift chambers with absorbers between.

The analysis was performed on data accumulated between July 1979 and December 1981 with a total integrated luminosity of 37.04 pb^{-1} at total center of mass energies between 27.2 and 36.7 GeV. The average center of mass energy was 34.2 GeV.

Monte Carlo simulations were used to determine selection criteria and their efficiency. In the simulation the following processes were considered: The new sequential heavy lepton is produced through the process

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

via single photon annihilation. Radiative corrections up to order α^3 were taken into account for the process (1) according to Berends et al. [8]. The electron-type neutral heavy lepton is produced through the process

$$e^+ + e^- \to E^0 + \bar{\nu}_e \quad \text{or} \quad \overline{E^0} + \nu_e \,, \qquad (2)$$

by W-boson exchange with V + A or V − A coupling [9]. The mass of the W-boson, on which the production cross sections depend, was assumed to be 75.2 GeV/c^2 ‡2. The leptons decay with the standard weak interaction [11]:

$$L \to \nu_L + \text{“W”} \hookrightarrow (ud), (cs), e\nu, \mu\nu, \text{ or } \tau\nu \,; \qquad (3)$$

$$E^0 \to e + \text{“W”} \hookrightarrow (ud), (cs), e\nu, \mu\nu, \text{ or } \tau\nu \,. \qquad (4)$$

The branching ratio to each channel was according to ref. [11]. It depends on masses of the leptons below 14 GeV/c^2. It is constant for heavy lepton masses above 14 GeV/c^2; approximately 35% for (ud), 35% for (cs), 10% for ($e\nu$), 10% for ($\mu\nu$), and 10% for ($\tau\nu$). In the hadronic decay channels the quarks were fragmented into mesons according to the scheme of Field and Feynman [12]: They were fragmented [13] according to the fragmentation function $f(z) = 1 - a + 3a(1-z)^2$, where $z = P/Eq$. The momenta of the secondary quarks transverse to the fragmentation axis were distributed according to $d\sigma \sim \exp(-p_t^2/2\sigma_q^2)d^2p_t$. Values of the fragmentation parameters were varied from 0.1 to 0.9 for a, from 250 MeV/c to 500 MeV/c for σ_q, and from 0.1 to 0.9 for r, where r is the ratio of the pseudoscalar mesons to all mesons. The analysis was designed to be insensitive to the details of the fragmentation.

Prior to detailed analyses, data were reduced in two different ways to “high-” and “low-multiplicity samples”. The selection criteria of the “high-multiplicity” sample were described in ref. [14]. In summary, they were as follows:

(1) Total barrel shower energy > 3.0 GeV or each end cap shower energy > 0.4 GeV.

(2) At least 4 tracks from the interaction region – excluding events with one isolated track and three tracks on the opposite side (typical event topology of the process $e^+e^- \to \tau^+\tau^-$).

Corresponding to the luminosity of 37.04 pb^{-1}, 20.3 K events were accumulated as the “high-multiplicity sample”. This sample consists of ordinary multi-

‡1 The mass limit of the $L^{\pm}$ decreased due to radiative corrections, which give a negative contribution near the production threshold.

‡2 The total cross section of E^0 is insensitive to the mass of $W^{\pm}$ [9]. Its production rate increases at most by 2% if one uses the mass 81 GeV [10] instead of 75.2 GeV, and our results do not change.

hadron events (~2/3) and two-photon-induced hadronic events (~1/3).

The requirements for the "low-multiplicity sample" were:

(1) At least one track with a momentum over 0.3 GeV/c and a polar angle greater than 37° to the $e^{\pm}$ beam directions.

(2) $E_{vis} > 0.1\, E_{cm}$, where E_{vis} and E_{cm} are the total visible energy of the event and the total center of mass energy of the reaction.

(3) The number of charged tracks to be minimum 2, maximum 8. It should be noted that this cut is wider than that in ref. [14]. The number of events in this sample was 192 K. The "high" and "low" multiplicity samples have considerable overlap.

Three different signatures were asked for, corresponding to three cases. These were: (a) "Acoplanar two-jet" for $L^{\pm}$ or E^0 ($\overline{E^0}$) with high mass ($\gtrsim 6$ GeV/c^2), (b) "one isolated track recoiling against a jet on the opposite side" for $L^{\pm}$ with low mass ($\lesssim 6$ GeV/c^2), and (c) "only one jet + nothing on the opposite side" for E^0 ($\overline{E^0}$) with low mass ($\lesssim 6$ GeV/c^2).

The selection criteria for these three cases are as follows:

(A) $L^{\pm}$ or E^0 ($\overline{E^0}$) with high mass. The processes considered here are:

$$e^+ + e^- \to L^{\pm} + L^{\mp}\,, \quad L \to \text{hadrons} + \nu_L, \quad L \to \text{anything} + \nu_L \tag{5}$$

$$e^+ + e^- \to E^0 + \bar{\nu}_e\,(\overline{E^0} + \nu_e)\,, \quad E^0 \to \text{hadrons} + e \tag{6}$$

As the expected masses of the heavy leptons are high, the final states of these processes should be multiprong events. Therefore the "high multiplicity sample" was used in this analysis. As already mentioned, this sample consists mostly of the ordinary multihadron events and the two-photon-induced hadronic events. The following cuts were applied to the data in order to remove these two sources of background:

(1) $0.33 < E_{vis}/E_{cm} < 1.0$.

(2) $|\cos\theta_{th}| < 0.7$, where θ_{th} is the polar angle of the thrust axis measured with respect to the beam direction [14]. Fig. 1a shows a scatter plot of the data in the plane of the E_{vis}/E_{cm} versus θ_{th}. It can be clearly seen that the multihadron events are distributed near $E_{vis}/E_{cm} \sim 1$ and that the two-photon events are clustered in the $|\cos\theta_{th}| \sim 1$ region with low E_{vis}/E_{cm}.

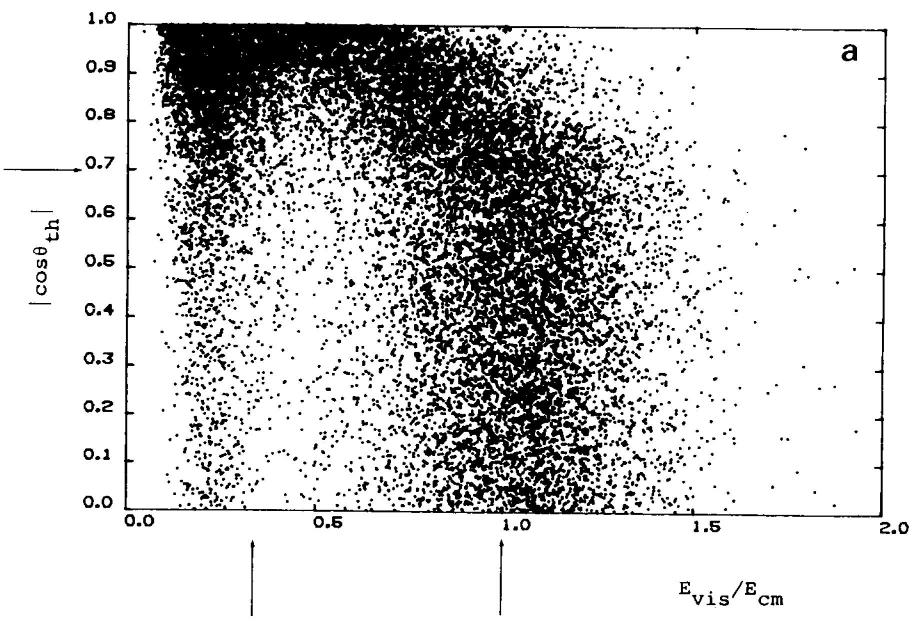
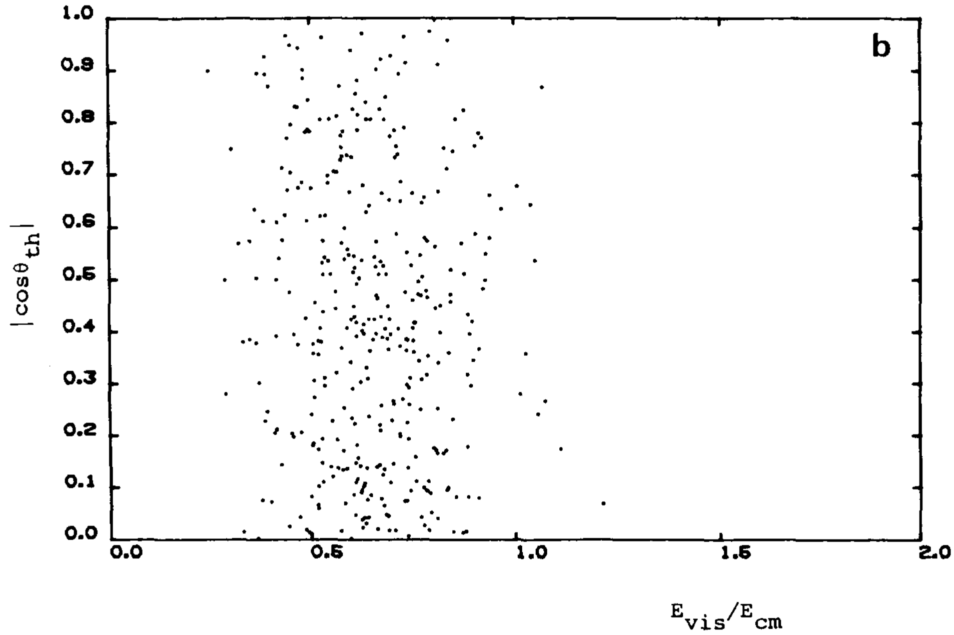


Fig. 1a.



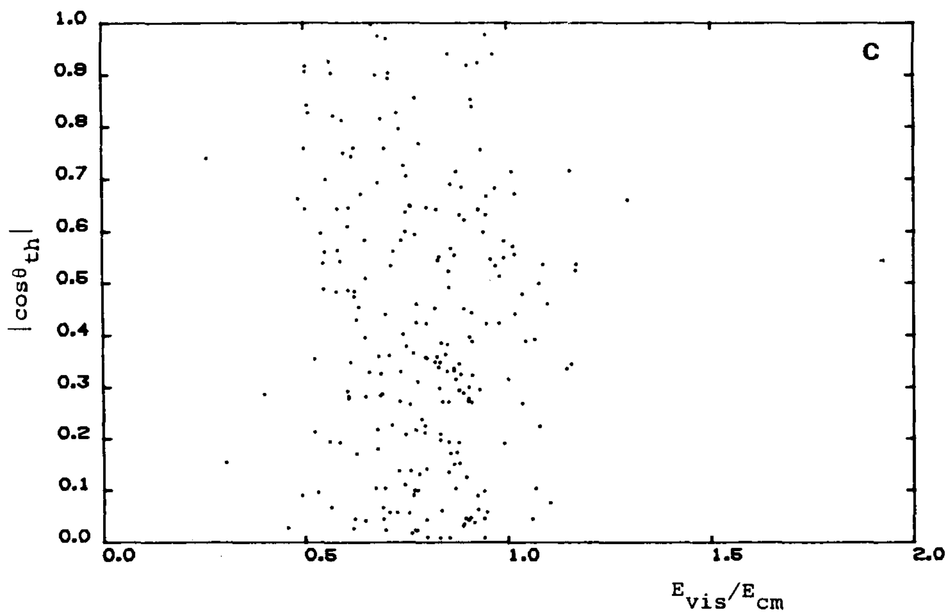


Fig. 1. (a) The scatter plot for the data in the E_{vis}/E_{cm} and $|\cos\theta_{th}|$ plane. Arrows indicate the cuts. (b) The corresponding plot for Monte Carlo simulated $L^{\pm}$ events with an assumed mass of 17.0 GeV/c^2 at a beam energy of 17.5 GeV. (c) The corresponding plot for the Monte Carlo simulated E^0 events, with V + A coupling and an assumed mass of 17.0 GeV/c^2 at a beam energy of 17.5 GeV.

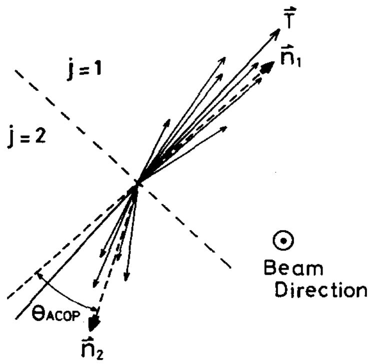


Fig. 2. An example of the thrust axis, $\boldsymbol{T}$, acoplanarity, θ_{ACOP}, and $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$, where the two hemispheres are divided by a dashed line.

Fig. 1b (1c) shows the corresponding plot of the Monte Carlo simulated events of the $L^{\pm}$ (E^0 with V + A) with a mass of 17.0 GeV/c^2 and E_{cm} = 35.0 GeV/c^2.

(3) Acoplanarity angle $\theta_{ACOP} > 50^\circ$, where the acoplanarity angle of a multiprong event is defined in the following way [14]:

$$\cos\theta_{ACOP} = \frac{-(\boldsymbol{n}_1 \times \boldsymbol{z})(\boldsymbol{n}_2 \times \boldsymbol{z})}{|\boldsymbol{n}_1 \times \boldsymbol{z}| \cdot |\boldsymbol{n}_2 \times \boldsymbol{z}|},$$

where $\boldsymbol{n}_1$ and $\boldsymbol{n}_2$ are the unit vectors pointing in the directions of the sums of the momenta in the two hemispheres (j = 1, 2) defined by the plane perpendicular to the thrust axis, $\boldsymbol{z}$ is the unit vector parallel to the direction of the positron beam. The acoplanarity angle is defined to be 180° when there are neither tracks nor photons in one of the hemispheres.

Fig. 2 shows the variables, $\boldsymbol{T}$, $\boldsymbol{n}_1$, and $\boldsymbol{n}_2$ of a typical event. Fig. 3 shows the acoplanarity distribution of the data and the simulations. The data do not agree with the distribution expected for $L^{\pm}$ nor for E^0. As seen in this figure, the observed acoplanarity distribution peaks sharply towards zero and its shape and absolute rate can be well explained by the normal multihadron events [15] ‡3.

In order to determine a lower mass limit, the expected and observed numbers of events are compared. The expected numbers of L^+L^- events determined with Monte Carlo simulations are shown in table 1. The expected numbers of E^0 or $\overline{E^0}$ with V + A and

‡3 Events were generated with the Lund Monte Carlo program from ref. [15].

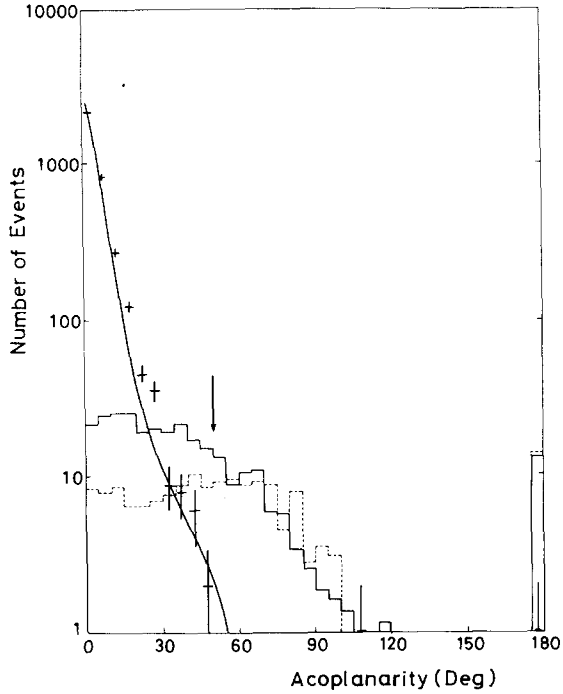


Fig. 3. The acoplanarity distribution for the data (points), Monte Carlo simulated multihadron events (solid curve), simulated $L^{\pm}$ events (solid line histogram), simulated E^0 with V + A coupling events (dashed line histogram). The leptons were generated with an assumed mass of 17.0 GeV/c^2 at a beam energy of 17.5 GeV. An arrow indicates the cut.

V − A coupling are shown in table 2 and table 3, respectively. Fig. 4 also shows the expected numbers: the solid line (A) for $L^{\pm}$, the dotted line (A) for E^0 with V + A, and the double dot–dashed line (A) for E^0 or $\overline{E^0}$ with V − A, respectively.

The systematic error comes mainly from the uncertainty in the hadron fragmentation and was estimated by varying the fragmentation parameters to be at most 10% for $L^{\pm}$. The systematic error for $\overline{E^0}$, which in addition contains contributions from first order radiative corrections, was estimated to be at most 20%. In determining the expected number of events the most pessimistic cases with maximum systematic errors were taken.

The number of actual observed events surviving the cuts was two, giving 6.3 events as 95% CL limit. The origin of the two events is unknown. However, the two events are consistent with the contribution from the

Table 1
Expected number of L^+L^- pairs produced, acceptance, and expected number of L^+L^- events surviving the final cuts (A) and (B) (see text) for various $L^\pm$ masses. Radiative corrections up to order α^3 are taken into account.

m_L (GeV/c^2)	# of $L^\pm$ produced	Acceptance		# of $L^\pm$ expected	
		A	B	A	B [a)]
2.0	3714.4		0.101		774.1
4.0	3505.6		0.153		936.7
6.0	3356.4		0.158		927.6
8.0	3200.5		0.162		917.5
10.0	2993.2		0.147		838.7
12.0	2679.3	0.136	0.090	363.9	639.5
13.0	2455.3	0.160	0.073	392.7	579.3
14.0	2158.2	0.179	0.032	386.3	468.0
15.0	1752.7	0.180		315.4	
16.0	1253.6	0.180		225.6	
17.0	460.2	0.180		82.8	
18.0	17.5	0.180		3.1	

[a)] The contributions from $\tau^+\tau^-$ (399 events) have been added.

process $e^+e^- \to$ hadrons + hard photon, where the photon escaped through a gap of the lead glass counter between the barrel and the endcap. The beam energies of the two events were 16.993 and 16.996 GeV. Since no $L^\pm$ candidate with mass above 17 GeV/c^2 was observed, 3.0 events as 95% CL limit was used in determining a lower limit of m_L above 17 GeV/c^2 (see dotted lines in fig. 4). A region of m_L between ~6.0 GeV/c^2 and 18.0 GeV/c^2 was excluded at more than 95% CL. The excluded regions of E^0 were between ~6.0 GeV/c^2 and 24.5 GeV/c^2 for V + A coupling and ~6.0 GeV/c^2 and 22.5 GeV/c^2 for V – A coupling at 95% CL.

Table 2
Expected numbers of $E^0\,\bar{\nu}_e$ produced with V + A coupling, acceptance, and expected number of $E^0\,\bar{\nu}_e$ events surviving the vinal cuts (A) and (C) (see text) for various E^0 masses.

m_{E^0} (GeV/c^2)	# of E^0 produced	Acceptance		# of E^0 expected	
		A	C	A	C
1.0	593.1		0.440		261.0
3.0	585.7		0.407		238.6
5.0	571.1		0.290		165.6
7.0	549.5	0.257	0.170	141.4	93.5
9.0	521.3	0.272	0.103	142.0	53.8
11.0	486.8	0.272	0.062	132.3	30.0
13.0	446.8	0.262	0.042	117.1	18.8
15.0	401.9	0.243		97.7	
17.0	353.2	0.214		75.6	
19.0	301.8	0.175		52.9	
21.0	248.8	0.130		32.5	
23.0	196.0	0.083		16.3	
25.0	145.0	0.039		5.7	

Table 3
Expected numbers of $E^0\,\bar{\nu}_e$ produced with V – A coupling, acceptance, and expected number of $E^0\,\bar{\nu}_e$ events surviving the final cuts (A) and (C) (see text) for various E^0 masses.

m_{E^0} (GeV/c^2)	# of E^0 produced	Acceptance		# of E^0 expected	
		A	C	A	C
1.0	216.9		0.358		77.7
3.0	214.8		0.330		70.9
5.0	210.5		0.240		50.5
7.0	204.0	0.231	0.135	47.1	27.6
9.0	195.5	0.246	0.072	48.0	14.0
11.0	184.8	0.247		45.6	
13.0	172.1	0.240		41.3	
15.0	157.4	0.224		35.3	
17.0	140.9	0.198		27.9	
19.0	122.9	0.162		19.9	
21.0	103.6	0.118		12.3	
23.0	83.5	0.073		6.1	
25.0	63.3	0.030		1.9	

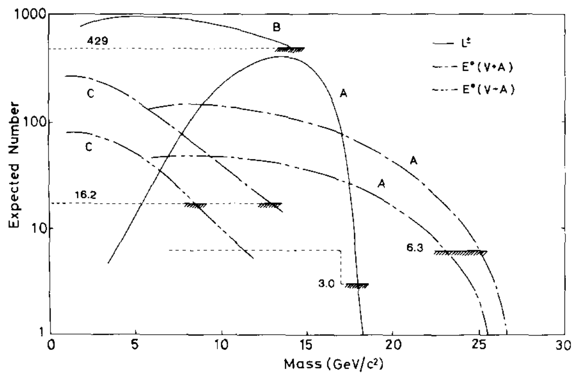


Fig. 4. Numbers of expected events of $L^\pm$ (solid lines A, B), E^0 with V + A coupling (dot–dashed lines A, C), and E^0 with V – A coupling (double dot–dashed lines A, C). A, B, and C are corresponding to the three cases, (A), (B), and (C) (see text). The 95% CL limits are also shown (hatched lines). A step of the dashed line at 17 GeV is due to the possible candidates. For details see text.

(B) $L^\pm$ with low mass. The process considered here is:

$$e^+ + e^- \to L^\pm + L^\mp . \qquad (7)$$
$$\quad L \to \text{hadrons} + \nu_L$$
$$\quad L \to e/\mu + \nu_L$$

For low mass $L^\pm$, the multiplicity of charged particles is expected to be small. Therefore the "low multiplicity sample" was used in this analysis.

The new heavy lepton candidates were selected by the following criteria:

(1) At least four good tracks were required.

(2) One isolated good track, which is separated by more than 90° from any other charged tracks, was required.

(3) The absolute momentum of the isolated track > 2 GeV/c.

(4) $|\cos\theta_{isol}| < 0.77$, where θ_{isol} is the polar angle of the isolated track.

(5) The shower energy deposited by the isolated track is less than 70% of the beam energy.

(6) $E_{vis}/E_{cm} > 0.33$.

(7) $|B_L| < 0.4$, where B_L is the momentum balance (the z component of the sum of all visible momenta divided by the total visible energy).

The cuts (4) and (5) were used to remove Bhabha events with an electro-magnetic shower on one side and two-photon-induced hadronic events where a beam electron or positron recoiled at a large angle. The cuts (6) and (7) were used to remove the two-photon hadronic events where the scattered electron and positron were not detected. The number of remaining events after the cuts was 435. Scanning this sample, 45 events were rejected as showering Bhabha events, cosmic showers and $\mu^+\mu^-$ + converted gamma. The number of candidate events was thus 390.

The contribution from $e^+e^- \to \tau^+\tau^-$ was estimated to be 399.0 from a Monte Carlo simulation. The observed number of events is consistent with this value. The expected numbers of events with $L^\pm$ are shown in table 1 and fig. 4 [solid line (B)]. Thus the production of $L^\pm$ is excluded in the mass region below 14.0 GeV/c^2 at more than 95% CL.

(C) E^0 ($\overline{E^0}$) with low mass. The process considered here is.

$$e^+ + e^- \to E^0 + \nu_e (\overline{E^0} + \nu_e) .$$
$$\quad E^0 \to \text{anything} + e$$

The candidates were selected by applying the following cuts to the "low-multiplicity sample":

(1) At least two good tracks.

(2) $|\cos\theta_{th}| < 0.7$, where θ_{th} is the polar angle of the thrust axis.

(3) $E_{vis}/E_{cm} > 0.4$.

(4) No energy flow outside a cone of 50° half angle from the jet direction.

The cut (2) was used to reduce the two-photon-induced events. The cuts (3) and (4) ensured selection of events with full beam energy on one side and nothing on the other side.

Ten events survived the cuts. These events can be attributed to the known process, $e^+e^- \to e^+e^-e^+e^-$. An E^0 with a mass between 1.0 GeV/c^2 and 13.0 GeV/c^2 (V + A) or between 1.0 GeV/c^2 and 8.5 GeV/c^2 (V − A) was excluded at more than 95% CL (see tables 2, 3, and fig. 4).

By combining the results (A) and (B), it is found that no sequential heavy lepton ($L^\pm$) exists with a mass below 18.0 GeV/c^2 at 95% CL. The results (A) and (C) imply 95% CL lower mass limits of 24.5 GeV/c^2 (22.5 GeV/c^2) for an electron-type neutral heavy lepton (E^0, $\overline{E^0}$) with V + A (V − A) coupling.

We are indebted to the PETRA machine group for their excellent support during the experiment and to all the engineers and technicians of the collaborating institutions who have participated in the construction and maintenance of the apparatus. This experiment was supported by the Bundesministerium für Forschung und Technologie, by the Education Ministry of Japan and by the UK Science and Engineering Research Council through the Rutherford Appleton Laboratory. The visiting groups at DESY wish to thank the DESY directorate for their hospitality.

References

[1] PLUTO Collab., Ch. Berger et al., Phys. Lett. 99B (1981) 489.
[2] MARK-J Collab., D.P. Barber et al., Phys. Rev. Lett. 45 (1980) 1904.
[3] TASSO Collab., R. Brandelik et al., Phys. Lett. 99B (1981) 163.

[4] J. Bürger, Intern. Symp. on Lepton and photon interactions at high energies (Bonn, 1981).
[5] J.L. Rosner, Nucl. Phys. B126 (1977) 124.
[6] D.I. Meyer et al., Phys. Lett. 70B (1977) 469.
[7] JADE Collab., W. Bartel et al., Phys. Lett. 88B (1979) 171.
[8] F.A. Berends and R. Kleiss, Nucl. Phys. B177 (1981) 237, and references therein.
[9] J.D. Bjorken and C.H. Llewellyn Smith, Phys. Rev. D7 (1973) 887;
F. Bletzacker and H.T. Nieh, Phys. Rev. D16 (1977) 2115;
K. Fujikawa, Phys. Rev. D17 (1978) 1841;
M. Gourdin and X.Y. Pham, Nucl. Phys. B164 (1980) 387.
[10] UA1 Collab., G. Arnison et al., Phys. Lett. 122B (1983) 103.
[11] Y.S. Tsai, Phys. Rev. D4 (1971) 2821; SLAC-PUB-2450 (1979).
[12] R.D. Field and R.P. Feynman, Nucl. Phys. B136 (1978) 1.
[13] See for example: JADE Collab., W. Bartel et al., Phys. Lett. 101B (1981) 129.
[14] JADE Collab., W. Bartel et al., Phys. Lett. 114B (1982) 211.
[15] T. Sjoestrand, LUND preprint LU TP 80-3 (1980).