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# HEAVY LEPTONS IN 1986*

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## INTRODUCTION

In this paper, presented at the XXIII International Conference on High Energy Physics, I update recent reviews[1,2] on the search for new leptons beyond the electron, muon, and tau generations. I also discuss an unexplored region in the mass ranges of leptons: small visible energy events in electron-positron annihilation and close-mass pairs.

## CHARGED LEPTONS: STABLE OR SEQUENTIAL

The traditional, comprehensive way[3,4] to search for charged leptons uses the reaction (Fig.1a)

$$e^+ + e^- \rightarrow \gamma_{virtual} \rightarrow L^+ + L^- \qquad (1)$$

If the $L^\pm$ is stable, this gives an easily recognized final state. If the $L^\pm$ is sequential, it can be recognized as the $\tau$ was found[4], through the decays

$$L^- \rightarrow \nu_L + \ell^- + \bar{\nu}_\ell \ , \quad \ell = e, \mu, \tau \qquad (2a)$$
$$L^- \rightarrow \nu_L + \text{hadrons} \qquad (2b)$$

This requires the mass, $m_{\nu_L}$, of the $L$ associated neutrino obey

$$m_{\nu_L} < m_L \qquad (3)$$

In existing searches, $m_{\nu_L}$ is supposed negligible compared to $m_L$, a point I return to at the end of the paper.

The lower limits obtained in $e^+e^- \rightarrow L^+L^-$ searches on a new stable or sequential lepton have not changed in the last year as summarized by Komamiya[1].

$$m_{L^\pm} \text{ (stable) } < 21.1 \text{ GeV/c}^2, 95\% \text{ CL} \qquad (4a)$$
$$m_{L^\pm} \text{ (sequential) } < 22.7 \text{ GeV/c}^2, 95\% \text{ CL} \qquad (4b)$$

First results using a new search method for sequential leptons (Fig.1e)

$$\begin{aligned} p + \bar{p} &\rightarrow W^- + \text{hadrons} \\ W^- &\rightarrow L^- + \bar{\nu}_L \\ L^- &\rightarrow \nu_L + \text{hadrons} \end{aligned} \qquad (5)$$

were reported[5] at this conference and in a recent preprint.[6] The search used the UA1 experiment at the CERN $\bar{p}p$ collider. The preliminary result is no new charged, sequential leptons with masses less than about 40 GeV/c$^2$.

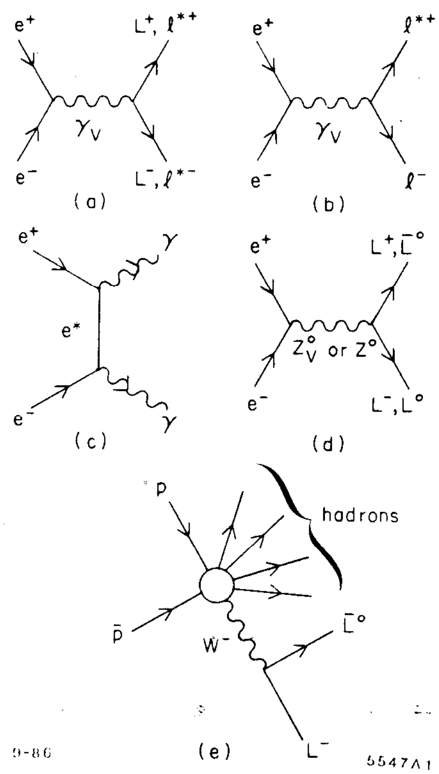


**Figure 1.**

## CHARGED LEPTONS: EXCITED

Charged leptons that decay electromagnetically

$$\ell^{*-} \rightarrow \ell^- + \gamma \ , \ \ell = e, \mu, \tau \quad ; \qquad (6)$$

(Fig.1a) usually called excited; can be produced and detected through[7,8]

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$$e^+ + e^- \rightarrow \ell^{*+} + \ell^{*-} \rightarrow \ell^+ + \ell^- + \gamma + \gamma \quad (7a)$$

and[7,8,9] (Fig.1b)

$$e^+ + e^- \rightarrow \ell^{*+} + \ell^- \rightarrow \ell^+ + \ell^- + \gamma \quad (7b)$$

The $e^*$ will also contribute[7] to

$$e^+ + e^- \rightarrow \gamma + \gamma \quad (7c)$$

through the diagram in Fig.1d. In this case and in the reaction in Eq.7b the cross section depends on the unknown constant $\lambda$ in the $\ell^* - \ell - \gamma$ vertex function, usually written

$$\text{Vertex Function } = e\left(\frac{\lambda}{2M_{\ell^*}}\right)\bar{u}_{\ell^*}\sigma_{\mu\nu}u_\ell F^{\mu\nu} \quad (8)$$

Thus searches using $ee \rightarrow \ell\ell\gamma$ or $ee \rightarrow \gamma\gamma$ are ambiguous if $\lambda$ is taken to be very small. Even a search using the reaction in Eq.7a can be made ambiguous by attributing a sufficiently small form factor $F_{\ell^*}$ to the $\ell^* - \ell^* - \gamma$ vertex.

No excited leptons have been found. Using the reaction in Eq.7a, $ee \rightarrow \ell^*\ell^* \rightarrow \ell\ell\gamma\gamma$, and assuming $F_{\ell^*}$ sufficiently close to 1., the CELLO experiment[7] at PETRA found the 95% CL mass limits:

$$M_{e^*} > 23.0 \text{ GeV/c}^2$$
$$M_{\mu^*} > 23.0 \text{ GeV/c}^2 \quad (9)$$
$$M_{\tau^*} > 22.7 \text{ GeV/c}^2$$

Mass limits using the reactions in Eqs.7b and 7c depend on $\lambda$. Figure 2 gives the recent results of the CELLO experiment on $M_{e^*}$; Fig.3 gives recent results from the JADE experiment[8] at PETRA on $M_{\tau^*}$. Other lower limits on $M_{e^*}$ and $M_{\mu^*}$ have been obtained by Grifols and Persis[10] using

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-, \bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \quad (10)$$

## NEUTRAL LEPTONS: NO GENERATION MIXING

Consider four types of neutral leptons: ($i$) an $L^0, L^-$ pair with the latter heavier

$$(L^0, L^-)\ , \quad M_- > M_0 \quad ; \quad (11a)$$

($ii$) an $L^0, L^-$ pair with the former heavier

$$(L^0, L^-)\ , \quad M_0 > M_- \quad ; \quad (11b)$$

($iii$) a pair of neutral leptons

$$(L^0, L^{0\prime})\ , \quad M_0 > M_{0'} \quad ; \quad (11c)$$

or ($iv$) an isolated neutral lepton

$$L^0 \quad (11d)$$

In the pair cases, assume the heavier member decays always to the lighter member plus other particles, and there is no mixing between this new pair and any other lepton or pair of leptons.

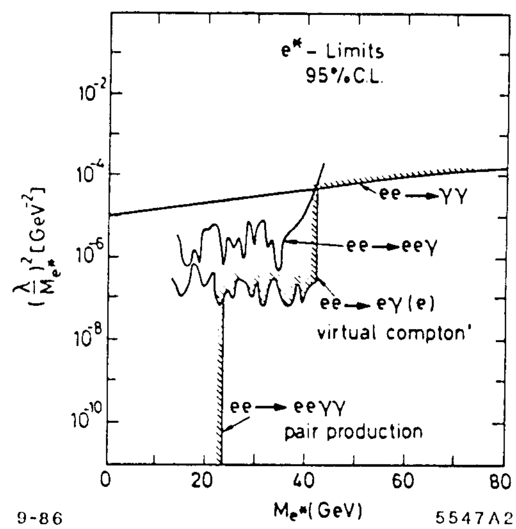


Figure 2.

Lepton types $ii$, $iii$ and $iv$ are the simplest extensions of the sequential lepton, type $i$, that preserve the observed no mixing between lepton generations. Yet searches for neutral leptons of these types are scattered and incomplete. This is because electron-positron colliders have not had sufficient energy to use effectively the comprehensive $L^0$ production reaction (Fig.1d)

$$e^+ + e^- \rightarrow Z^0_{real\ or\ virtual} \rightarrow L^0 + \bar{L}^0 \quad (12)$$

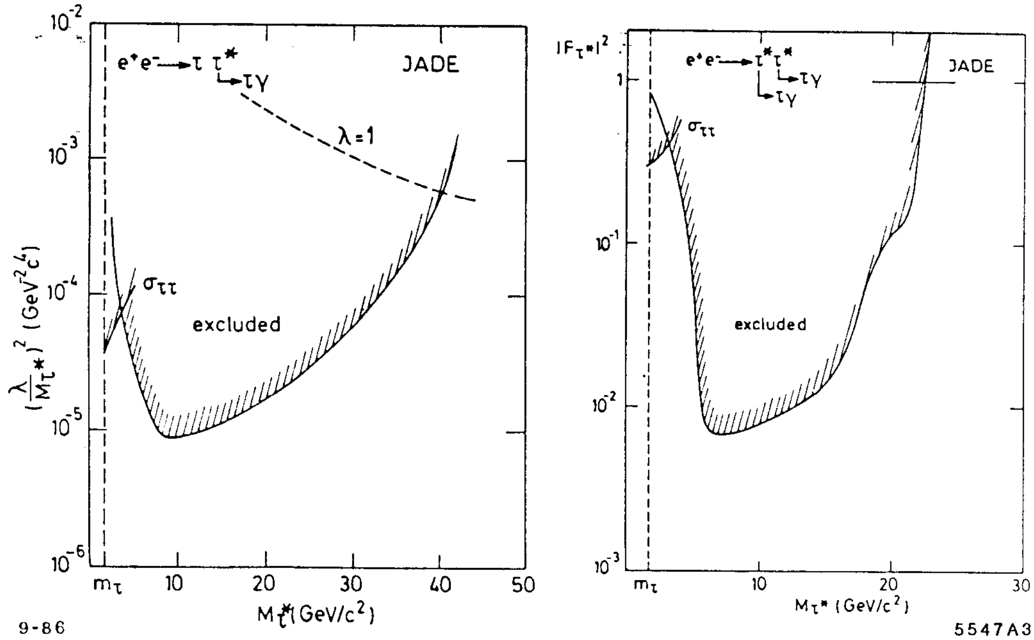


**Figure 3.**

I know of only four experimental restrictions on the mass, $m_0$, of neutral leptons if there is no generation mixing.

($a$) Since there are no new sequential charged leptons with $m_- < 22.7$ GeV/c$^2$, Eq.4b, there are no new type $i$ neutral leptons with $m_0 \lesssim 22.7$ GeV/c$^2$. (See the last section of this paper for a restriction on this statement.)

($b$) If an $L^0$ is of type $ii$, then from Eqs.4a and 11b, $m_0 \gtrsim 21.1$ GeV/c$^2$.

($c$) Type $iii$ $L^0$'s, not allowed in standard weak interaction theory, are limited by the null results of a search by Perl *et al.*[11]

($d$) An upper limit on the total number of small mass $L^0$'s with normal weak interaction coupling is obtained from the width of the $Z^0$ or from the total cross section for the reaction

$$e^+ + e^- \to \gamma + L^0 + \bar{L}^0 \qquad (13)$$

Here $L^0$ includes $\nu_e, \nu_\mu$, and $\nu_\tau$. These limits are discussed by Whitaker[12] in these proceedings.

Definitive searches for neutral leptons will be carried out in the next five years at TRISTAN, the SLAC Linear Collider (SLC), and LEP using the reaction in Eq.12.

## NEUTRAL LEPTONS: GENERATION MIXING

Another extension of the sequential lepton model, which I find less attractive,[13] is mixing between lepton generations. This allows an $L^0 - W - \ell^-$ coupling where $\ell$ is an $e, \mu$, or $\tau$. There are then numerous ways to find the $L^0$, I give some examples taking $\ell = e$.

($a$) Electron spectrum in meson decay:

$$\pi^- \to e^- + L^0 \quad , \quad K^- \to e^- + L^0 \qquad (14)$$

($b$) $L^0$ production via meson decay and subsequent $L^0$ decay:

$$\begin{aligned} D^- &\to \bar{L}^0 + e^- + \text{hadrons} \\ \bar{L}^0 &\to e^+ + \text{particles} \end{aligned} \qquad (15)$$

($c$) $L^0$ pair production via $e^+e^-$ annihilation and subsequent $L^0$ decay

$$\begin{aligned} e^+ + e^- &\to L^0 + \bar{L}^0 \\ L^0 &\to e^- + \text{particles} \end{aligned} \qquad (16)$$

(*d*) $L^0 - \bar{\nu}_e$ production via $e^+e^-$ annihilation and subsequent $L^0$ decay

$$e^+ + e^- \to L^0 + \bar{\nu}_e$$
$$L^0 \to e^- + \text{particles} \qquad (17)$$

A thorough review of all such searches has been done by Gilman.[2] Additional searches are reported in Refs.14 and 15. There is no evidence for the existence of neutral leptons that have generation mixing. Some searches extend to about 35 GeV/c$^2$, the method in Eq.17 being used. The sensitivity of the various searches depends on $U$, the ratio of the strength of the $L^0 - W - \ell^-$ vertex to the standard $\nu_\ell - W - \ell^-$ vertex. $|U|^2$ values as small as $10^{-8}$ has been explored, but in some $L^0$ mass regions the minimum values of $|U|^2$ are about $10^{-2}$.

## SMALL VISIBLE ENERGY EVENTS IN $e^+e^-$ ANNIHILATION

Experimental studies at storage rings of electron-positron interactions in the range of 10 to 50 GeV total energy ($E_{tot}$) mostly fall into two classes: (I) annihilation interactions or (II) two-virtual-photon interactions. Annihilation interactions take place through

$$e^+ + e^- \to \gamma_{virtual} \text{ or } Z^0_{virtual} \to \text{particles} \quad . \qquad (18a)$$

It is conventional to also include in class I the reactions

$$e^+ + e^- \to e^+ + e^- \qquad (18b)$$

and

$$e^+ + e^- \to \gamma + \gamma \qquad (18c)$$

Class II, the two-virtual photon interactions, mostly contains

$$e^+ + e^- \to e^+ + e^- + \ell^+ + \ell^- \ , \ \ell = e, \mu, \tau \qquad (19a)$$

and

$$e^+ + e^- \to e^+ + e^- + \text{hadrons} \qquad (19b)$$

Much of the time the final $e^+$ and $e^-$ are produced at small angles to the beam line and are not detected in the main part of the apparatus. Hence most class II events have small visible energy, relative to $E_{tot}$. The visible energy, $E_{vis}$, is the sum of the energy in the charged tracks and the energy of the photons which convert in the electromagnetic calorimeters.

In the $E_{tot}$ range of 10 to 50 GeV, the cross section for class II events is much larger than the cross section for class I events. Therefore most experimental studies of class I interactions require that the events in the data sample have $E_{vis} > E_{vis,min}$, where $E_{vis,min}$ is a minimum acceptable value of $E_{vis}$. In events with just two charged particles $E_{vis,min}$ may be as small as several GeV, but in studies of hadron production via annihilation $E_{vis,min}$ may be as large as $E_{tot}/4$.

Consider the production of a pair of charged particles

$$e^+ + e^- \to x^+ + x^- \qquad (20a)$$

and suppose the $x^\pm$ has three properties:

(i) The $x^-$ decays through the weak interaction to an $x^0$

$$x^- \to x^0 + \text{other particles} \qquad (20b)$$

(ii) The $x^0$ is stable.

(iii) The masses of the $x^-$ and $x^0$, $m_-$ and $m_0$ respectively, are close to each other. For example

$$m_- - m_0 \lesssim 2 \text{ GeV/c}^2 \qquad (21)$$

Then the reaction sequence in Eq.20 may produce events with $E_{vis}$ values too small to be accepted in class I studies. On the other hand such events may be difficult or impossible to find when the criteria for class II studies are applied, because of the large cross sections of conventional class II events.[17]

Thus a process described by Eq.20 with the mass condition of Eq.21 could remain undetected in present electron-positron interaction studies.

## CLOSE-MASS LEPTON PAIRS

Searches for a new sequential charged lepton, $L^-$, have assumed the associated neutral lepton, $L^0$, has negligible mass compared to the $L^-$ mass. I recently began to consider the effect on the sensitivity of these searches of $m_0$ being close to $m_-$, for example, the effect of the mass condition in Eq.21. A thorough reevaluation is required of the data used for the searches, the analysis being carried out with $m_0$ allowed to vary; we have just started such an analysis using data from the Mark II detector at PEP. However data published for other purposes can be used to sketch the region in $m_-$ and $m_0$ values which requires exploration.

It is convenient to use a plot, Fig.4, with the mass difference

$$\delta = m_- - m_0$$

and the $L^-$ mass, $m_-$. Four regions can be excluded.

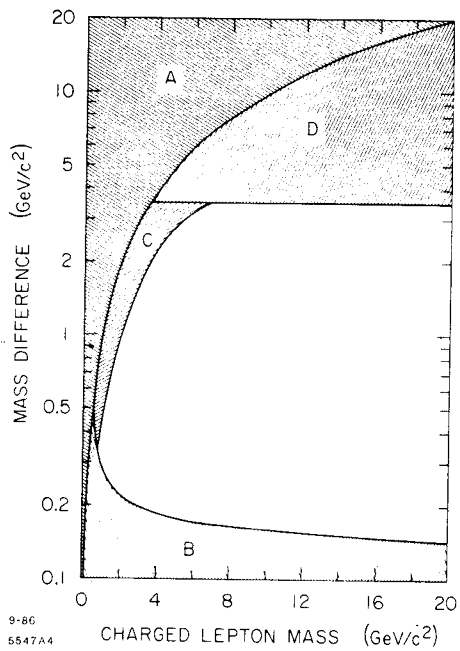


**Figure 4.**

Region A: By definition $\delta \leq m_-$, therefore the $\delta > m_-$ region is excluded.

Region B: Assuming the usual V-A weak interaction, when $\delta$ is of the order of the pion mass or smaller, the $L^-$ decay length becomes of the order of a meter or longer. Therefore many of the $L^\pm$ would appear stable in the JADE collaboration searches[1,18] at PETRA for stable leptons. Using this observation and the 21.1 GeV/c$^2$ lower mass limit in Eq.4a, Region B is excluded.

Region C: Consider the decay $L^- \to L^0 + a + b + \ldots$ In the $L^-$ rest frame the $L^0$ energy is

$$E^0 = (m_-^2 + m_0^2 - m^2)/2m_- \qquad (22)$$

where $m$ is the invariant mass of the set of particles $a + b + \ldots$ The searches already carried out for sequential leptons would not be sensitive to a small change in $E^0$, say 20% or 30%, from the standard $m_0 = 0$ case. To be conservative, say 20%. Then the null results of the searches are still true for $m_0^2 \lesssim 0.2\ m_-^2$. This gives the boundary of Region C. The boundary position is conservative, probably the boundary should be more to the right.

Region D. The JADE collaboration[18] has looked for the supersymmetric particles called charginos with decays

$$\begin{aligned} \tilde{\chi}^- &\to \tilde{\gamma} + \ell^- + \bar{\nu}_\ell \\ \tilde{\chi}^- &\to \tilde{\gamma} + \text{hadrons} \end{aligned} \qquad (23)$$

where $\tilde{\chi}^-$ is the chargino and $\tilde{\gamma}$ is a stable photino. In this search the $\tilde{\gamma}$ was allowed to have a nonzero mass, and $\tilde{\chi}^- - \tilde{\gamma}$ mass differences as small as 3 GeV/c$^2$ were explored. Decay kinematics are similar for $\tilde{\chi}^-, \tilde{\gamma}$ pairs and $L^-, L^0$ pairs with the same masses. Therefore I use this null chargino search to set an upper limit $\delta > 3.5$ GeV/c$^2$ for the $L^-, L^0$ case. This forms the lower boundary of Region D.

Figure 4 shows the region of $\delta$ and $m_-$ were an $L^- - L^0$ pair might exist and not have been found if the $L^0$ were stable. I emphasize that the boundaries of this region were deduced crudely from other people's data. The true unexplored region may be smaller or longer. Figure 4 should be regarded as a guide to what needs to be done in looking for a sequential lepton pair with a nonzero mass neutral member.

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