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THE STATUS OF HEAVY LEPTON SEARCHES[*†]

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ABSTRACT

This paper reviews searches for heavy leptons using e^+e^- annihilation, lepton-hadron collisions, photon-hadron collisions, hadron-hadron collisions, and studies of macroscopic matter. The present experimental status and future possibilities are summarized.

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TABLE OF CONTENTS

I. INTRODUCTION

This talk reviews lepton searches which have been carried out since the discovery of the tau lepton, and it looks ahead to the searches which can be carried out in the next few years.

After a discussion of the lepton concept in Sec. II, I describe the comprehensive charged lepton searches using e^+e^- annihilation which have been carried out principally at the PETRA e^+e^- colliding beams facility. This section, Sec. III, is longer than the later sections because before discussing each e^+e^- search, I summarize the ideas associated with the type of lepton sought. Lepton searches depending upon e^+e^- annihilation via the weak interaction are discussed in Sec. IV.

Major efforts have also been made to find new leptons using neutrino-hadron collisions (Sec. V.A) and charged lepton-hadron collisions (Sec. V.B). Photon-hadron collisions have not been used much for lepton searches in the recent past; however the concept is briefly described in Sec. VI.

Hadron-hadron collisions (Sec. VII) hold the most promise but it is intrinsically the most difficult method. The promise is high because of the large barycentric energies available when the new pp and $\bar{p}p$ colliding beams facilities begin to operate. The intrinsic difficulty is how to find a new lepton buried in a 10^8 or larger background of hadronic productions.

In Sec. VIII I briefly discuss lepton searches using macroscopic quantities of matter.

I have not reviewed two subjects because of my complete lack of experience in these subjects. One subject is cosmic ray searches[1] for leptons. The other is limits on numbers and properties of leptons from cosmology.[2]

Since this review concerns experimental work carried out since 1974 or 1975, I have omitted most experimental references previous to those years in the interest of brevity. A 1974 review paper[3] by Rapidus and myself contains many earlier references. Similarly most theoretical references are after those years, although I occasionally go back to 1970 or 1971. I have listed in Table I some general theoretical papers that I have tended to use; these have a "t" in the reference. Other theoretical references appear with the experimental ones.

II. THE CONCEPT OF A LEPTON

The original concept of a lepton was a spin-½, small-mass particle (compared to the pion mass) which did not interact through the strong force. The discovery of the τ removed the mass restriction. I will first list the elements of the conventional concept, and then discuss possible deviations.

Conventional Concept of a Lepton

At present we call a particle a lepton if:

(a) the particle does not interact through the strong interactions;

(b) the particle interacts through the weak interactions;

(c) the particle has no internal structure and no internal constituents;

(d) there is a particle-type conservation law associated with the particle; and

(e) the spin of the particle is ½.

Possible Deviations from the Conventional Concept

Requirements (a) and (b) are intrinsic to the concept of a lepton. For example, a particle without strong and without weak interactions would be an "electromagnetic" particle like the photon.

Requirement (c) says that the lepton must be a point particle; its spatial extent is entirely due to the range of the forces through which it interacts. All the known leptons fulfill the point particle requirements. However we can conceive of a lepton with structure or with internal constituents, that is, a composite lepton. It would then act like a proton in reactions, would have a non-unit form factor, but would still satisfy a particle-type conservation law.

Requirement (d) is exemplified by the sequential lepton model, Sec. III.C. A weaker form of lepton-type conservation is the excited electron (e^*) model, Sec. III.D. Here the e^{*-} has the same lepton number as the e^-, so that the same lepton number is carried by the ν_e, e^- and e^{*-}. However one can violate requirement (d) and conceive of a lepton without a lepton-type conservation property. For example, a large mass ℓ^+ lepton might decay via $\ell^+ \rightarrow$ proton + γ. Yet if the ℓ^+ obeyed requirements (a), (b), (c) and (e), we would still call it a lepton.

Requirement (e), the spin being ½, is not essential. Indeed in Sec. III.F we discuss spin-0 leptons. However if we remove requirements (d) and (e), then we have no way to distinguish a lepton from the proposed $W^{\pm}$ and Z^{o} intermediate bosons, since the $W^{\pm}$ and Z^{o} satisfy requirements (a), (b) and (c).

Obviously, the concept of a lepton is empirical; we should keep the concept general so that our search for new leptons is general. The basic idea is that the particle have weak interactions but not strong interactions. Indeed this is the old penetrating particle idea which led Anderson and Neddermeyer to the discovery of the muon

III. CHARGED LEPTON SEARCHES USING e^+e^- ANNIHILATION VIA THE ELECTROMAGNETIC INTERACTION

A. History of e^+e^- Searches

I have already noted that this is not an historical review. However, lepton searches using e^+e^- annihilation have so far been the most fruitful, and it is important to trace the development concept. That development falls into three periods:

(1) Pioneer work using ADONE

The use of e^+e^- annihilation to look for new leptons goes back to the pioneer work of Zichichi and his colleagues,[4] and the work of Orito et al.,[5] at the Frascati ADONE e^+e^- storage ring. This work began in about 1967.

(2) Discovery of the τ

The second period began in 1974-1975 with the discovery[6] of the τ at SPEAR. The major work at DORIS and SPEAR on the confirmation of the existence of the τ and the study of its properties extended until 1978-1979.[7]

(3) Comprehensive heavy lepton searches at PETRA

In 1979 the experiments at PETRA began to search comprehensively for heavy leptons. Their results are described in Secs. III and IV. They have now been joined by experiments at PEP and CESR. At the same time studies of the properties of the τ are continuing at these storage rings.

B. Pair Production Cross Sections

In Secs. III.C through III.G I discuss searches for new charged leptons produced through the one photon exchange process (Fig. 1)

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow L^+ + L^- \quad . \tag{1}$$

If we assume L has unit electric charge, conventional electromagnetic properties, and a point particle nature, the cross section is

$$\text{spin-0:} \quad \sigma = \frac{\pi\alpha^2\beta^3}{3E^2_{\text{c.m.}}} \tag{2a}$$

$$\text{spin-}\tfrac{1}{2}\text{:} \quad \sigma = \frac{2\pi\alpha^2\beta\left(3-\beta^2\right)}{3E^2_{\text{c.m.}}} \tag{2b}$$

Here $E_{\text{c.m.}}$ is the total center-of-mass energy and β is the velocity of the L. For spin-1 or greater[t29-t34] the production cross section for the diagram in Fig. 1 violates the unitarity limit at sufficiently high energy. Therefore other diagrams must enter, as is the case in $e^+e^- \rightarrow W^+W^-$ where W is the proposed spin-1 intermediate boson.[8] Or the lepton must have a form factor, $F(E_{\text{c.m.}})$, which decreases as $E_{\text{c.m.}}$ increases; then the cross sections in Eq. (2) are multiplied by $F^2(E_{\text{c.m.}})$.

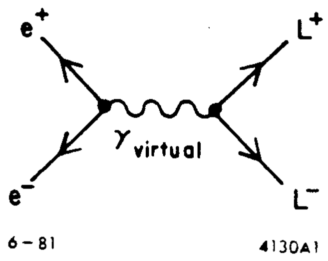


Fig. 1. Diagram for $e^+e^- \rightarrow L^+L^-$.

Ignoring these problems:

$$\text{spin-1} \qquad \sigma = \frac{\pi \alpha^2 \beta^3}{3m_L^2}\left[1 + \frac{3}{4}\left(1 - \beta^2\right)\right] \tag{2c}$$

$$\text{spin-3/2} \qquad \sigma = \frac{4\pi \alpha^2 \beta \; E_{c.m.}^2}{27m_L^4} + \text{lower order terms in } E_{c.m.}^2 \tag{2d}$$

The power in using Eq. 1 to search for charged leptons is that the production cross section depends upon reasonable assumptions about the electromagnetic properties of the leptons, but does not depend upon the weak interaction properties. As we shall see in the next few sections, assumptions about weak interaction properties can widely vary.

For future use we remind the reader of the often used relative cross section

$$R\left(e^+e^- \to L^+L^-\right) = \sigma\left(e^+e^- \to L^+L^-\right)/\sigma\left(e^+e^- \to \mu^+\mu^-\right) \tag{3}$$

For spin ½ leptons

$$R\left(e^+e^- \to L^+L^-\right) = \beta\left(3 - \beta^2\right)/2 \tag{4}$$

C. Charged Sequential Leptons

Since the discovery of the τ the concept of a charged sequential lepton, $L^{\pm}$, has become well known. In this concept[t1-t9] the charged lepton L^- and its associated neutrino, ν_L, share a unique, conserved lepton number. Taking the L to be more massive than the ν_L (the converse case is discussed in Sec. IV.A), the L decays only through the weak interaction:

$$L^- \rightarrow \nu_L + e^- + \bar{\nu}_e$$
$$L^- \rightarrow \nu_L + \mu^- + \bar{\nu}_\mu \qquad (5a)$$
$$L^- \rightarrow \nu_L + \tau^- + \bar{\nu}_\tau$$

and

$$L^- \rightarrow \nu_L + (\text{hadrons})^- \qquad (5b)$$

Figure 2 shows a rough way to estimate the branching fractions. Noting that all the quark modes produce hadrons; ignoring the Cabibbo supposed decay channels such as $\bar{u}s$, $\bar{c}d$ and $\bar{u}b$; and ignoring mass threshold effects; the predicted branching fractions are

$$B\left(L^- \rightarrow \nu_L e^- \bar{\nu}_e\right) \approx B\left(L^- \rightarrow \nu_L \mu^- \bar{\nu}_\mu\right) \approx B\left(L^- \rightarrow \nu_L \tau^- \bar{\nu}_\tau\right) \approx 0.1 \qquad (6a)$$

$$B\left(L^- \rightarrow \nu_L \text{hadrons}\right) \approx 0.7 \qquad (6b)$$

These fractions assume the L-ν_L mass difference is above about 4 GeV/c^2. For smaller mass difference, the branching fractions approach those of the τ:

$$B\left(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e\right) \approx B\left(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu\right) \approx 0.17 \quad , \qquad (7)$$

with the remainder going to the hadronic modes.

Several methods have been used in the comprehensive searches[9-12] carried out at PETRA for sequential changed leptons heavier than the τ. They are summarized by Wiik.[13] Some of the methods used are:

1) Look for a μ or e well separated in angle from a particle jet, and large missing momentum. This would come from

$$L^\pm \rightarrow \mu^\pm \left(\text{or } e^\pm\right) + 2 \text{ neutrinos}$$

plus

$$L^\mp \rightarrow 5\text{-or-more charged hadrons} + \text{neutrino} \quad .$$

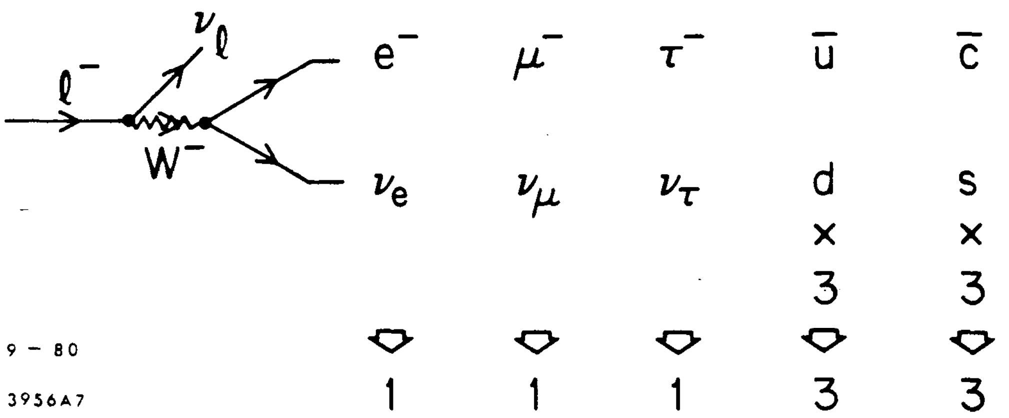


Fig. 2. Crude method for calculating heavy lepton branching fractions.

2) Look for any single charged particle well separated in angle from a particle jet, and large missing energy. Here the e or μ in 1) need not be identified.

3) Look for a jet of particles in one hemisphere and no particles in the other hemisphere. This assumes the decay products of one of the L's have gone outside the detector acceptance.

4) Look for two very non-coplanar particle jets and large missing momentum. Here both L's have decayed hadronically.

5) Searches for mass below about 5 GeV/c^2 require a method different from 1) - 4), above. Such an $L^\pm$ will decay like a τ. Hence one looks for an enhancement in the apparent $e^+e^- \to \tau^+\tau^-$ cross section.

No sequential leptons beyond the tau have been found; the mass limits are given in Table II. One obvious comment: this null conclusion assumes the production cross section of Eq. (2b); if the production cross section for a mysterious reason were less than 1/10 that size, the searches would be ineffective.

Searches for higher mass charged sequential leptons will obviously continue as e^+e^- colliding beams facilities reach higher energies. The searches will get more tedious because the production cross section for Eq. (1) decreases as $E_{c.m.}^{-2}$. However, assuming conventional, weak interaction theory,[8] the reaction $e^+e^- \to Z^0 \to L^+L^-$ will provide an enhanced cross section at $E_{c.m.} = M_{Z^0}$ for $M_L < M_{Z^0}/2$ (see Sec. IVC).

D. Excited Leptons

It is an old idea[3,14,t15-t17] to look for excited electrons, e^*, or muons, μ^*, which decay via

$$e^{*\pm} \to e^{\pm} + \gamma \qquad (8a)$$
$$\mu^{*\pm} \to \mu^{\pm} + \gamma$$

and now one can add the excited τ:

$$\tau^{*\pm} \to \tau^{\pm} + \gamma \quad . \qquad (8b)$$

Once again the pioneer e^+e^- searches were done at the ADONE e^+e^- colliding beams facility.[15-17] There are two ways in which an e^* can be produced in e^+e^- annihilation. Figure 3a shows the conventional process

$$e^+ + e^- \to \ell^{*+} + \ell^{*-} \quad , \qquad (9)$$

and Fig. 3b shows the unconventional process

$$e^+ + e^- \to \ell^{*\pm} + \ell^{\mp} \qquad (10)$$

Consider first Eq. (9) which has the cross section of Eq. (2), assuming the ℓ^* is a point particle. Recently, K. Hayes[19,20] used data from the Mark II detector at SPEAR to search for e^* and μ^*. A lower limit on the masses of 3.3 GeV/c^2 was set. Table III gives the upper limits on R. Of course, PEP and PETRA experimenters can search to much higher masses, and such searches are now being done.

We consider next Eq. (10) which enables the search to extend to $m_{\ell^*} \approx E_{c.m.}$, a big advantage over Eq. (9). Unfortunately the ℓ^*-γ-ℓ vertex in Fig. 3b cannot be represented[14,18,t15-t17] by the

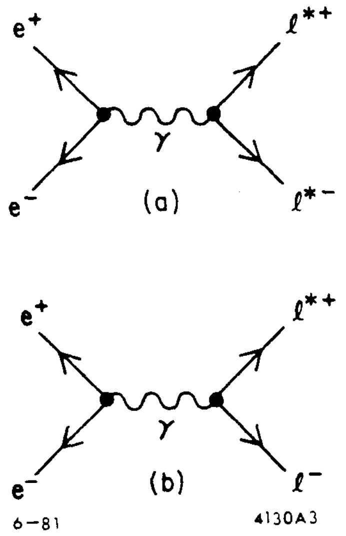


Fig. 3. Diagrams for (a) $e^+e^- \to \ell^{*+}\ell^{*-}$ and (b) $e^+e^- \to \ell^{*+}\ell^-$.

conventional electromagnetic current

$$J^\mu = e\, \bar{u}_\ell\, \gamma^\mu\, u_{\ell^*} \tag{11}$$

because the current is not conserved if $m_{\ell^*} \neq m_\ell$. One must use an unconventional coupling such as

$$J^\mu = \frac{e}{\Lambda}\, \bar{u}_\ell \left(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right) u_{\ell^*}\, k_\nu \tag{12}$$

Here Λ, which has mass units, is the inverse of some coupling parameter e'/e. The mass unit is required by the presence of k_ν, the photon four-momentum, in the numerator. (Remember we use units with $c = 1$). In modern theories, Eq. (12) is regarded as a phenomenological representation of some more complicated vertex, perhaps involving the weak interaction, Fig. 4.

There are many processes which can produce an ℓ^*, or can be affected by the existence of an ℓ^*. Figure 5 shows several. A crude indication of the effects of Λ is also given. It is clear that as Λ increases, all cross sections and effects decrease. Hence the lower limits on m_{ℓ^*}, which I give next, all assume an upper limit on Λ.

1) $e^+ + e^- \to \ell^{*\pm} + \ell^\mp$: This process was considered in the pioneer ADONE searches.[15-17] The Mark J experimenters[21] at PETRA have used it to set a lower limit on the μ^* mass of 35 GeV/c^2.

2) $e^+ + e^- \to \gamma + \gamma$: This diagram [22] has been recently applied to PETRA data[13] on the $e^+e^- \to \gamma\gamma$ to set a lower limit on the e^* mass of about 40 or 50 GeV/c^2.

3) Measurement of $(g_\ell - 2)/2$: The ℓ^* contribution to $(g-2)/2$ is logarithmically divergent in lowest order, hence another unknown

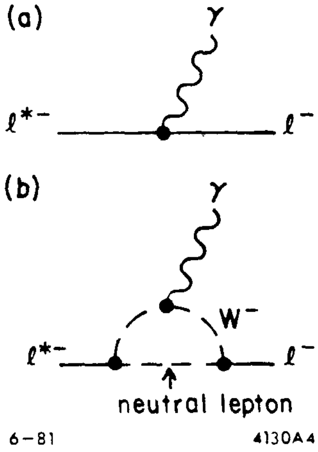
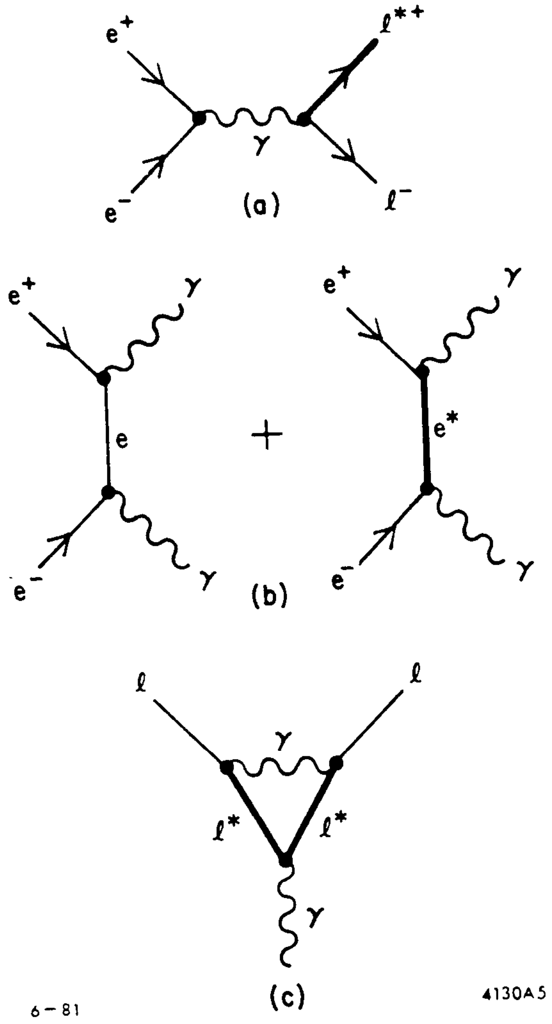


Fig. 4. Diagrams for (a) the ℓ^*-γ-ℓ vertex and (b) a weak interaction process which yields ℓ^*-γ-ℓ.



$\sigma(ee \rightarrow \ell^* \ell) \sim \frac{\alpha^2}{\Lambda^2}$ (threshold factor)

$\sigma(ee \rightarrow \gamma\gamma)$ contains terms in $\frac{E^2_{c.m.}}{\Lambda^2}$, $\frac{m^2_{\ell *}}{\Lambda^2}$, etc.

lowest order contribution to $\frac{(g_\ell - 2)}{2}$ is $\sim \frac{3\alpha\, m_\ell\, m_{\ell *}}{\Lambda^2} \log\left(\frac{\lambda}{m_{\ell *}}\right)$

Fig. 5 Diagrams and crude formulas showing the effect of an ℓ^* on (a) $e^+e^- \rightarrow \ell^{*+}\ell^-$, (b) $e^+e^- \rightarrow \gamma^+\gamma^-$ and (c) the value of $(g_\ell-2)/2$.

constant λ is required. In addition, the ℓ^* contribution is more divergent in higher order.[21] Therefore there has been no rigorous use of the diagram to set limits on m_{ℓ^*}, in spite of the very precise measurements[23,24] of g_e-2 and $g_\mu-2$. Incidentally, vacuum polarization (Fig. 6) can be rigorously calculated because it depends on the ℓ^*-γ-ℓ^* vertex. The recent $g_\mu-2$ measurement[23,24] gives a lower limit on the ℓ^* mass of 0.21 GeV/c^2.

E. Charged Ortholeptons and Paraleptons[t10-t14]

In the past there has been considerable discussion of heavy leptons which share the lepton number of a less massive lepton family.[t10-t13] Using the e^-,ν_e as the example for the less massive lepton family, an electron-associated charged ortholepton, E_o^-, would have the lepton number of the e^- and ν_e. (Such heavy leptons are of particular interest in searches using lepton-hadron collisions because they could be produced copiously as discussed in Sec. V).

If the E_o^- decay is dominated by the electromagnetic decay

$$E_o^- \rightarrow e^- + \gamma \quad , \qquad (13)$$

then the E_o^- acts like an excited electron. That model has already been discussed. Here I will consider the model where the electromagnetic decay is sufficiently suppressed to allow the weak interaction to dominate the decay process. Then the ortholepton, E_o^-, decays through the charged weak current giving

$$\begin{aligned} E_o^- &\rightarrow \nu_e + \ell^- + \bar{\nu}_\ell \\ E_o^- &\rightarrow \nu_e + (\text{hadrons})^- \end{aligned} \qquad (14)$$

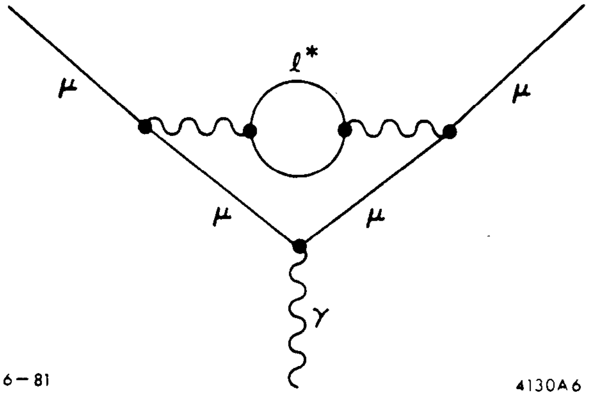


Fig. 6 Contribution of the ℓ^* to $(g_\mu-2)/2$ through vacuum polarization.

or through the neutral weak current giving

$$E_o^- \rightarrow e^- + \nu_\ell + \bar{\nu}_\ell$$

$$E_o^- \rightarrow e^- + (\text{hadrons})^0 \quad . \qquad (15)$$

Here ℓ means e, μ or τ.

The charged, electron-associated, paralepton, E_p^-, would have the lepton number of e^+. Electromagnetic decay is forbidden and the charged current weak decay modes are

$$E_p^- \rightarrow \bar{\nu}_e + \ell^- + \nu_\ell$$

$$E_p^- \rightarrow \bar{\nu}_e + (\text{hadrons})^- \qquad (16)$$

The decay $E_p^- \rightarrow e^+$ + anything would require an unconventional doubly charged weak current in first order. Incidentally, the symbol M is usually used for a μ-associated ortholepton or paralepton.

I have not seen any comprehensive discussion of the application of the PETRA sequential lepton searches to charged ortholeptons and paraleptons. However, assuming conventional weak interactions, the decay modes in Eqs. (14) and (16) are analogous to the decay modes for sequential leptons in Eq. (5). Hence I believe the limits on sequential lepton masses given in Table II are by and large applicable to ortholeptons and paraleptons.

F. Spin-0 Charged Leptons

One can conceive of a spin-0 lepton with decay modes

$$e_s^\pm \rightarrow e^\pm + \nu$$

$$\mu_s^\pm \rightarrow \mu^\pm + \nu \qquad (17a)$$

where the subscript s indicates a scalar; or one can use some recent ideas of supersymmetry,[25] and assume the existence of an e_s or μ_s which decays via

$$\begin{aligned} e_s^{\pm} &\rightarrow e^{\pm} + \text{photino or goldstino} \\ \mu_s^{\pm} &\rightarrow \mu^{\pm} + \text{photino or goldstino} \end{aligned} \tag{17b}$$

Since the photino and goldstino have spin-½ and have only weak interactions, the decays in Eqs. (17) are experimentally indistinguishable.

The e^+e^- annihilation production cross section is given by Eq. (2a), which is a factor of four smaller than the spin-½ cross section at $\beta = 1$. The signature for

$$e^+ + e^- \rightarrow e_s^+ + e_s^- \text{ or } \mu_s^+ + \mu_s^- \tag{18}$$

is straightforward; the events consist of an e^+e^- or $\mu^+\mu^-$ pair with a large amount of missing momentum. Several searches have been carried out at PETRA, but no spin-0 leptons have been found.[26,27] The lower limits on the mass are given in Table II.

G. Other Charged Leptons

Since the discovery of the τ, searches for charged leptons have emphasized sequential or spin-0 types. However, one can consider other charged lepton types, some of which could be difficult to find. I'll mention four ideas.

1) Stable or long-lived charged leptons: This possibility is severely limited by PETRA searches[21,29] for the two-body process $e^+ + e^- \rightarrow a^+ + a^-$ where the particle a is not an e or μ. The Mark J collaboration[21] has set a lower limit on the mass of 14 GeV/c^2

for unit charge and lifetime greater than 17 ns. The Jade collaboration[29] has set a lower limit on the mass of 12 GeV/c^2 for a lifetime greater than 2 ns and various charges.

2) Leptons which decay with little visible energy: Consider, for example, an $L^{\pm}$ with a mass of 10 GeV/c^2 which shares a unique, conserved lepton number with a 9.5 GeV/c^2 neutral lepton L^o. All the dominant decay modes have one charged particle:

$$L^- \to L^o + e^- + \nu_e \ , \quad L^o + \mu^- + \nu_\mu \ , \quad L^o + \pi^- \ . \qquad (19)$$

Hence events from $e^+e^- \to L^+L^-$ would have two, very-low-momentum charged tracks, and would not be distinguishable from events produced through the two-virtual-photon reactions[28]

$$e^+e^- \to \left(e^+ + e^-\right) + e^- + e^-, \ \left(e^+ + e^-\right) + \mu^+ + \mu^-, \ \left(e^+ + e^-\right) + \pi^+ + \pi^- \ . \quad (20)$$

In these reactions the $e^+ + e^-$ in parenthesis often remain undetected because they are produced at very small angles to the beam directions, and the remaining two particles often have very low momentum.

3) Fractionally charged leptons: A lepton with a sufficiently small fractional charged q might remain undiscovered because the production cross sections in Eq. (2) are proportional to q^2, or it might remain undiscovered because q is too small to produce a signal in conventional charged particle detection devices. The search for fractionally charged particles made by W. Bartel et al.,[29] at PETRA is relevant here. For $q \geq 2/3$ of a unit charge they have excluded particles with masses less than 12 GeV/c^2. A lower energy null search using SPEAR data has been reported by Weiss et al.[30]

4. Leptons with unconventional dominant decay modes: Leptons whose dominant decay modes are unconventional might be missed in conventional searches. For example, Meyer et al.,[31] looked for

$$L^o \rightarrow e^{\pm} + \pi^{\mp}$$

or

$$L^o \rightarrow \mu^{\pm} + \pi^{\mp} \qquad ,$$

the L^o coming from the decay of a τ. They excluded the mass range of 0.5 to 1.5 GeV/c^2.

IV. LEPTON SEARCHES USING e^+e^- ANNIHILATION VIA THE WEAK INTERACTION

A. Neutral Heavy Leptons

There are types of neutral heavy leptons analagous to most types of charged leptons.

1) Unique, conserved lepton number: In analogy to sequential charged leptons, we can consider a neutral lepton, L^o, with a less massive charged partner $L^{\pm}$ or neutral partner ν_L. The possible, lowest order, purely leptonic decay modes are

$$\begin{aligned} L^o &\rightarrow \nu_L + \ell^+ + \ell^- \\ L^o &\rightarrow L^- + \ell^+ + \nu_\ell \end{aligned} \tag{21a}$$

where ℓ = e, μ or τ. The semileptonic decay modes are

$$\begin{aligned} L^o &\rightarrow \nu_L + (\text{hadrons})^o \\ L^o &\rightarrow L^- + (\text{hadrons})^+ \end{aligned} \tag{21b}$$

Branching fraction calculations are analogous to those for sequential charged leptons. For example, if the only less massive partner is the L^-, the decay modes

$$L^o \rightarrow L^- + e^+ + \nu_e \ , \quad L^- + \mu^+ + \nu_\mu \ , \quad L^- + \tau^+ + \nu_\tau \qquad (22)$$

will each have a branching fraction of about 0.1. Of course this assumes the $L^o - L^-$ mass difference is above 4 GeV/c^2.

2) Nonunique lepton number: In analogy to the ortholepton and paralepton concept, the L^o could share lepton number with a less massive changed lepton. For example, if it has the same lepton number as the e^- and ν_e, the decay modes are

$$\begin{aligned} L^o &\rightarrow \nu_e + e^+ + e^- \\ L^o &\rightarrow \nu_e + (\text{hadrons})^o \\ L^o &\rightarrow e^- + (\text{hadrons})^+ \end{aligned} \qquad (23)$$

3) Stable: Of course, there is also the possibility of a stable, heavy, neutral lepton.

B. Pair Production Using the Neutral Current

In contrast to the progress in e^+e^- annihilation searches for charged heavy leptons which has been made in the last fifteen years, there has been little progress in neutral heavy lepton searches. This is because the process analogous to Eq. (1) is (Fig. 7a)

$$e^+ + e^- \rightarrow Z^o \rightarrow L^o + \bar{L}^o \qquad (24)$$

and that cross section is very small in the energy range of existing e^+e^- storage rings.

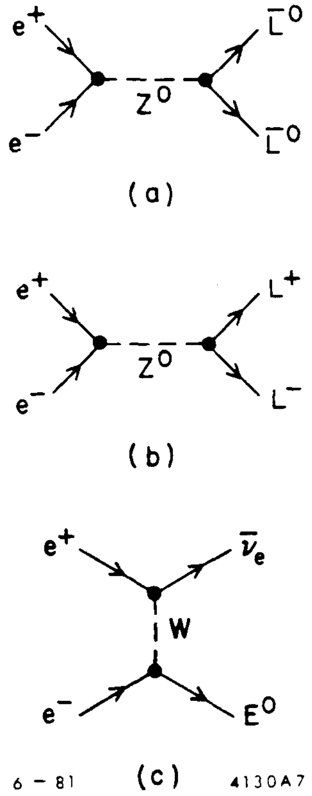


Fig. 7. Diagrams for e^+e^- production of lepton pairs through the weak interactions: (a) $e^+e^- \to L^0\bar{L}^0$, (b) $e^+e^- \to L^+L^-$, (c) an unconventional process.

I will use conventional Weinberg-Salam theory[8] to estimate this cross section. Although our immediate interest is in the neutral leptons, the next set of formulas are equally applicable to charged leptons, Fig. 7b. Hence I omit the subscript 0.

$$\sigma_{WI}\left(e^+e^-\rightarrow L\bar{L}\right) = \frac{G_F^2 E_{c.m.}^2}{96\pi} \frac{M_Z^4}{\left(E_{c.m.}^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2} \left[v_e^2+a_e^2\right]\left[v_L^2+a_L^2\right] [T] \quad (25)$$

Here G_F is the Fermi weak interaction coupling constant ($1.02 \times 10^{-5}/M_{proton}^2$), M_Z is the Z^o mass which we take as 90 GeV/c^2, and Γ_Z is the Z^o width. a and v are the coupling constants as defined by Ellis;[8] for example $a_e = -1$ and $v_e = -1 + 4\sin^2\theta_W$. [T] is a threshold factor which takes account of the nonzero mass of the lepton.

Applying Eq. (25) at PETRA and PEP energies ($E_{c.m.} \leq$ 40 GeV) we simplify as follows:

$$M_Z >> E_{c.m.}$$

$$\left[v_e^2 + a_e^2\right] \approx 1 \quad (26)$$

$$\left[v_L^2 + a_L^2\right] \approx 1$$

Of course the last approximation is speculative because the weak interaction coupling of the L is not known. Then

$$\sigma_{WI}\left(e^+e^- \rightarrow L\bar{L}\right) = \frac{G_F^2 E_{c.m.}^2}{96\pi} \quad (27a)$$

$$\sigma_{WI}\left(e^+e^- \rightarrow L\bar{L}\right) = \frac{G_F^2 E_{c.m.}^4}{128\pi^2\alpha^2} \approx 2.0 \times 10^{-9}\ E_{c.m.}^4 \quad (27b)$$

where $E_{c.m.}$ is in GeV. At a typical PETRA or PEP energy of $E_{c.m.} = 35$ GeV:

$$\sigma_{WI}\left(e^+e^- \rightarrow L\bar{L}\right) = 21 \times 10^{-37} \text{ cm}^2 \tag{28a}$$

$$R_{WI}\left(e^+e^- \rightarrow L\bar{L}\right) = 0.003 \tag{28b}$$

The R_{WI} in Eq. (28b) is very small compared to $R(e^+e^- \rightarrow \gamma \rightarrow L\bar{L}) = 1$. Therefore at PETRA and PEP energies it is very difficult to make neutral lepton searches using Eq. (24); but it is not impossible. Recent improvements in the working luminosity of e^+e^- storage rings, including the introduction of low-beta interaction regions, make it possible to accumulate 100,000 nb^{-1} of luminosity per year and per experiment. Using Eq. (28a) this would yield

$$e^+e^- \rightarrow L^o\bar{L}^o \text{ events per year } = 20 \quad .$$

In a few years, the combined results of several experiments could provide a comprehensive search for neutral leptons with masses less than 17 GeV/c^2.

C. Pair Production at the Z^o

The situation improves enormously if the e^+e^- colliding beams machine can reach the Z^o mass. This has been discussed many times[8,32,33] and I will summarize the search situation at the Z^o mass. Again, $L\bar{L}$ means L^+L^- or $L^o\bar{L}^o$. If $2m_L < m_{Z^o}$

$$\sigma_{WI}\left(e^+e^- \rightarrow L\bar{L}\right) = \frac{G_F^2}{96\pi} \frac{M_Z^4}{\Gamma_Z^2} \left[v_e^2+a_e^2\right]\left[v_L^2+a_L^2\right] [T] \quad . \tag{29}$$

This equation comes from Eq. (25) with $E_{c.m.} = M_Z$. We have ignored the L^+L^- production via a virtual photon.

Using

$$\begin{aligned} \left[v_e^2+a_e^2\right] &\approx 1 \\ \left[v_L^2+a_L^2\right] &\approx 1 \quad . \end{aligned} \tag{30}$$

Eq. (29) reduces to

$$\sigma_{WI}\left(e^+e^- \to L^+L^-\right) \approx \frac{G_F^2 M_Z^4}{96\pi\Gamma_Z^2} \, [T] \tag{31}$$

$$\sigma_{WI}\left(e^+e^- \to L^+L^-\right) \approx \frac{G_F^2 M_Z^6}{128\pi^2\alpha^2\Gamma_Z^2} \, [T] \tag{32}$$

Finally using

$$\begin{aligned} [T] &\approx 1 \\ M_Z &= 90 \text{ GeV}/c^2 \\ \Gamma_Z &= 2.5 \text{ GeV} \end{aligned}$$

we obtain

$$\sigma_{WI}\left(e^+e^- \to L\bar{L}\right) \approx 1.4 \times 10^{-33} \text{ cm}^2 \tag{33a}$$

$$R_{WI}\left(e^+e^- \to L\bar{L}\right) \approx 130 \quad . \tag{33b}$$

Eq. (33b) is an enormous improvement over Eq. (28b).

Next we calculate the luminosity required for a heavy lepton search. We need one hundred identified events to establish a new lepton. Assuming that 5% of the produced new lepton pairs can be so identified, we need 2000 produced lepton pairs. If the search is to be done in one year, we require

$$2000 \ \frac{L\bar{L} \text{ pairs}}{\text{year}} \cdot \frac{1 \text{ year}}{200 \text{ days}} \cdot \frac{1 \text{ day}}{10^5 \text{ sec}} = 10^{-4} \ \frac{L\bar{L} \text{ pairs produced}}{\text{sec}} \quad .$$

Thus we need a luminosity of

$$\mathscr{L} \approx \left(10^{-4}/\mathrm{sec}\right)/\left(1.4 \times 10^{-33}\ \mathrm{cm}^2\right)$$
$$\approx 10^{29}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$$

There are now several proposals for building e^+e^- colliding beams facilities which can attain 100 or more GeV and luminosities in excess of $10^{30}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$. Hence if conventional weak interaction theory is correct, these facilities can operate at the Z^o resonance and allow comprehensive searches for new leptons.

D. Unconventional Production Using the Weak Interaction

The ortholepton and paralepton concepts allow the possibility that a neutral lepton could be produced by an unconventional weak interaction process. Figure 7c is an example. The precise strength of the coupling at the upper vertex depends on the particular weak interaction theory used; such a theory would, of course, have to extend beyond Weinberg-Salam theory.

The JADE collaboration has carried out an interesting search[9] at PETRA for an e-associated E^o assuming the process in Fig. 7c. They look for the decay mode

$$E^o \rightarrow e + \text{leptons or hadrons} \quad .$$

Depending on the precise production mechanism, they set a 95% confidence lower limit on the E^o mass of 14.4 to 18.5 GeV/c^2.

V. LEPTON SEARCHES USING LEPTON-HADRON COLLISIONS

A. Neutrino-Hadron Collisions

The concept of using neutrino-hadron collisions to produce new leptons is intriging for two reasons. First, the method is equally applicable to neutral and charged lepton searches. Second, it is a natural idea to use the weak interaction to produce new leptons. However, there is a penalty. Since both the production and the decay processes depend on the weak interaction properties of the sought lepton,[t10-t14, t18-t20] the significance of a null search is highly dependent on what one assumes for those properties.

Consider Fig. 8 in which an incident neutrino, ν, produces an L^- heavy lepton. The cross section depends upon what one assumes for the ν-L coupling. In the most favorable situation the ν and L have the same lepton number and couple through the conventional weak coupling constant. In this situation the cross section would have the same magnitude as conventional weak interactions, and the production of L would be copious providing there was sufficient energy to generate the mass at the L^-. In a less favorable situation, the ν-L coupling would be weaker than conventional for unknown reasons, and the significance of the search is model dependent. In a very unfavorable situation the ν and L might have different lepton numbers. The process in Fig. 8 can then only occur in higher order and a very small production cross section is expected.

Since this is the first time I have discussed fixed target searches in this paper, I will make an obvious but important remark on the lepton

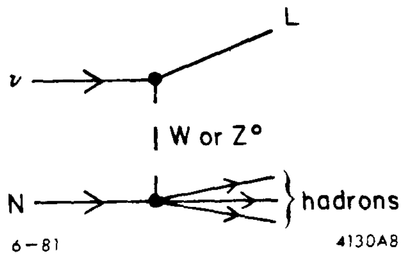


Fig. 8. Production of leptons in ν-hadron collisions.

mass range. For an incident particle of energy E, the maximum available mass is $\sqrt{2Em_p}$ where m_p is the proton mass. Kinematic and dynamic effects reduce this available range by a factor of 2. Hence

$$\text{available } m_L \lesssim \sqrt{E/2} \;\; \text{GeV}/c^2 \;, \quad E \text{ in GeV} \;. \tag{34}$$

For example, if E = 400 GeV, available $m_L \lesssim 14$ GeV.

Turning now to the experimental work in neutrino-hadron collisions: as you know, the lepton searches have not yielded positive results, in spite of extensive work and some hints of new things. I will note two recent typical searches and then remark on some unfinished business.

1) $\underline{\nu_\mu \rightarrow L^\pm \text{ search}}$: Cnops et al.,[34] have made a lepton search using pictures from the neon-hydrogen filled, 15-foot bubble chamber at Fermilab, the exposure being to a wideband ν_μ beam having a maximum energy of about 200 GeV. They assume the processes

$$\nu_\mu + N \rightarrow L^\pm + \text{hadrons} \tag{35a}$$

$$L^\pm \rightarrow e^\pm + \nu + \nu \quad . \tag{35b}$$

The production process, Eq. (35a), will have the highest cross section if the ν_μ-L^+ or ν_μ-L^- vertex is given the Fermi coupling constant. Hence the $L^\pm$ is a μ-associated ortholepton or paralepton. The decay process, Eq. (35b), will have a branching fraction of 0.1 to 0.2, as discussed in Sec. III.E. With these assumptions, they find

$$m_{L^-} \geq 7.5 \text{ GeV}/c^2 \;, \qquad m_{L^+} \geq 9. \text{ GeV}/c^2 \quad .$$

Barish et al.,[35] earlier set a similar L^+ limit

$$m_{L^+} \geq 8.4 \text{ GeV}/c^2 \quad .$$

2) <u>$\nu_\mu \rightarrow L^o$</u>: Kirch[36] has searched for neutral leptons using pictures from the CERN narrow band ν_μ beam in the BEBC bubble chamber. The chamber was filled with neon-hydrogen, and the maximum ν_μ energy was 220 GeV. The following reaction and decay sequence was assumed.

$$\nu_\mu + n \rightarrow L^o + \text{hadrons} \tag{36a}$$

$$L^o \rightarrow \mu^- + \mu^+ + \nu_\mu \tag{36b}$$

or

$$L^o \rightarrow \mu^- + e^+ + \nu_e \quad .$$

If the ν_μ-L^o vertex is given the Fermi coupling constant, the 90% confidence lower limit

$$M_{L^o} \geq 4.4 \text{ GeV}/c^2$$

if found.

3) <u>Unfinished business</u>: In the past decade of neutrino work, there have been occasional hints of strange things in the data. None of these hints have developed into an accepted and confirmed body of experimental data. However, this review would not be complete without an allusion to a few of these hints, perhaps regarded as "unfinished business."

A substantial amount of work has been done[37-39] on trimuon production in neutrino-hadron collisions:

$$\nu_\mu + n \rightarrow \mu^- + \mu^+ + \mu^- + \text{hadrons} \quad . \tag{37}$$

Such events could be a signature for heavy lepton production. However, within experimental error, the production cross section and properties of these events are explained by conventional production mechanisms.

Another signature for heavy lepton production is the production of a μe pair. Reference 40 is an example of an unresolved problem concerning μe events.

B. Charged Lepton-Hadron Collisions[t21-t23]

There are two mechanisms for heavy lepton production in charged lepton-hadron collisions.[t21-t23] We shall use μ^- - hadron collisions as the example.

1) The weak interaction mechanism is shown in Fig. 9a

$$\mu^- + N \rightarrow L + \text{hadrons} \qquad (38)$$

2) The virtual-photoproduction mechanism, Fig. 9b, uses the Bethe-Heitler process, Sec. VI.A, and will not be discussed here.

Returning to the weak interaction mechanism, the search considerations are analogous to those employed in neutrino-hadron collisions searches, Sec. V.A. Charged lepton searches have the advantage of providing a higher average incident energy. They have the disadvantage of larger backgrounds due to electromagnetic production of hadrons.

An example of a recent search is that of Clark et al.,[41] who looked for μ-associated leptons via

$$\mu^{\pm} + N \rightarrow L + \text{hadrons} \quad , \qquad (39a)$$

$$L^0 \rightarrow \mu^- + \mu^+ + \nu \quad . \qquad (39b)$$

They set a lower limit of

$$M_{L^0} \geq 9.\ \text{GeV}/c^2 \quad .$$

They set the same limit for a doubly charged lepton

$$L^{++} \rightarrow \mu^+ + \mu^+ + \nu \quad . \qquad (39c)$$

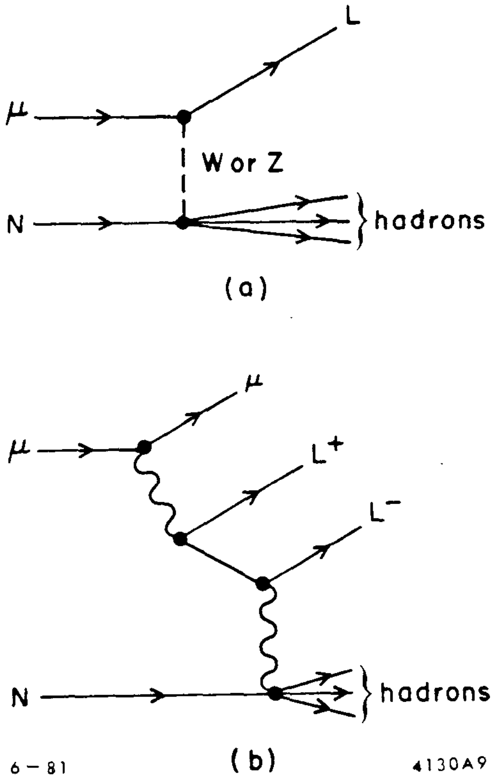


Fig. 9. Production of leptons in μ-hadron collisions via (a) the weak interaction and (b) virtual photoproduction.

Incidentally, a recent study[42] of μ-produced trimuon events

$$\mu^+ + N \rightarrow \mu^+ + \mu^- + \mu^+ + \text{hadrons} \qquad (40)$$

does not report any unconventional events.

C. Searches Using Electron-Proton Colliding Beams

There are now several proposals for constructing electron-proton colliding beams facilities. The proposed electron energy, E_e, is 10 to 30 GeV, and the proposed proton energy, E_p, is 300 to 800 GeV. Using the centers of those ranges, the barycentric energy is

$$E_{c.m.} \approx \sqrt{4E_eE_p} \approx \sqrt{4 \cdot 20 \cdot 500} = 200 \text{ GeV}$$

Comparing this to the discussion leading to Eq. (34),

$$\text{available } m_L \lesssim 100 \text{ GeV}/c^2 \quad .$$

Thus electron-proton colliders allow an enormous extension in the mass range of lepton searches using charged lepton-proton collisions. Obviously both mechanisms described in the previous section are available.

VI. LEPTON SEARCHES USING PHOTON-HADRON COLLISIONS

A. Bethe-Heitler Production of Charged Leptons

In photon-hadron collisions, as in e^+e^- annihilation, there is a well understood electromagnetic process for producing charged leptons. That is the Bethe-Heitler mechanism,[t24-t26] Fig. 10. As an example consider the calculated cross section[t26] for $\tau^+\tau^-$ production on Be by 500 GeV photons

$$\sigma\left(\gamma + \text{Be} \rightarrow \tau^+ + \tau^- + \text{hadrons}\right) \approx 3 \times 10^{-33} \text{ cm}^2 \quad . \qquad (41)$$

Compare this to the total cross section

$$\sigma(\gamma + \text{Be} \rightarrow \text{hadrons}) \approx 5 \times 10^{-28} \text{ cm}^2 \qquad (42)$$

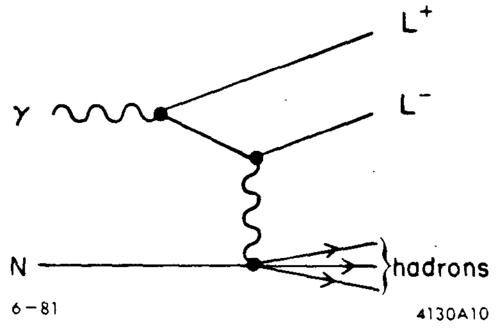


Fig. 10. Bethe-Heitler production of L^+L^- pairs.

which is 10^5 times larger. As of yet there has been no serious attempt to find τ pair photoproduction because of this overwhelming hadronic cross section.

The search for heavier leptons is even more difficult because the pair production cross section decreases as m_L increases.[t24-t26] crudely

$$\sigma\left(\gamma + N \rightarrow L^+ + L^- + \text{hadrons}\right) \sim m_L^{-2} \tag{43}$$

The most appealing method for finding L^+L^- pairs is to look for $\mu^\pm e^\mp$ pairs via

$$\begin{aligned} \gamma + \text{nucleus} &\rightarrow L^+ + L^- + \text{hadrons} \\ L^+ &\rightarrow e^+ + \text{neutrinos} \\ L^- &\rightarrow \mu^- + \text{neutrinos} \end{aligned} \tag{44}$$

Unfortunately the photoproduction of charm particle pairs also leads to $\mu^\pm e^\mp$ pairs through the semileptonic decay of both charm particles. The $\mu^\pm e^\mp$ signal from charm will be 10^2-10^3 times larger than the $\mu^\pm e^\mp$ signal from lepton pair production

Given these experimental difficulties and the null results of the PETRA searches, Sec. III, it does not appear to be fruitful to search for charged heavy leptons using photoproduction. For example, a photon beam with energies above 500 GeV is required to exceed the lower mass limit imposed by PETRA searches of about 15 GeV/c^2. However, it would be nice to detect the photoproduction of τ pairs just to make sure we understand the nature of τ.

B. Electron Beam Dump Experiments

The very high intensity, > 10^{14} e/sec, of the SLAC primary electron beam provides opportunity for searching for stable or long-lived neutral leptons in a beam dump experiment. In such an experiment, Fig. 11a, the electron beam interacts completely in a dense target called the dump. A long shield absorbs all photons, charged particles and hadrons. Neutral penetrating particles are detected in a massive detector through their weak interaction. The presumed production mechanism would be real or virtual photoproduction of a charged particle pair

$$\gamma + N \rightarrow A^{+} + A^{-} + \text{hadrons} \quad , \tag{45a}$$

and the subsequent decay of the A in the dump or shield

$$A \rightarrow L^{o} + ? \tag{45b}$$

The particle A might be a hadron or lepton. Other more indirect or unconventional production processes might be envisaged.

The pioneer electron beam dump experiment was done by M. Schwartz and his colleagues[43] in about 1970, and this reference is still interesting. For almost ten years nothing further was done in this direction. At present a new electron beam dump experiment[44] is being constructed at SLAC. It's immediate purpose is to search for penetrating, neutral particles which decay in flight, Fig. 11b. Such a particle could be a long-lived, but not stable, neutral lepton.

VII. LEPTON SEARCHES USING HADRON-HADRON COLLISIONS

A. Heavy Lepton Production Mechanisms

Heavy lepton searches using hadron-hadron collisions have two potential advantages. First, proton-proton and antiproton-proton colliding beams machines offer the highest energy range for searches. Second, proton dump experiments offer the possibility of using production

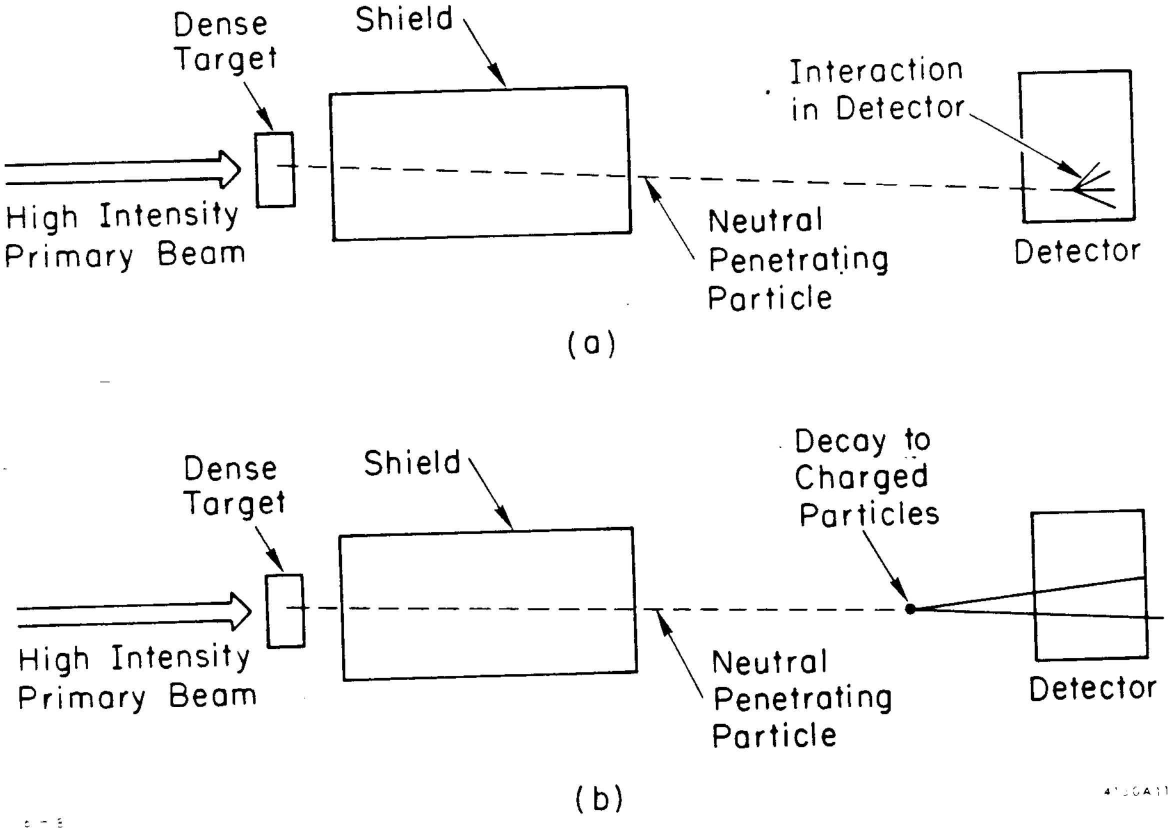


Fig. 11. Beam dump experiments.

processes with very small cross sections. Of course, both these advantages are compromised by the enormous background from conventional hadron-hadron processes.

There are several fairly obvious production mechanisms:

1) Charged lepton pair production through the Drell-Yan mechanism: Charged lepton pairs can be produced in hadron-hadron collisions through the quark-antiquark annihilation process[t27-t28]

$$q + \bar{q} \rightarrow L^+ + L^- \quad . \qquad (46a)$$

Bhattacharya et al.,[t27] give some theoretical predictions for the cross section for

$$p + p \rightarrow L^+ + L^- + \text{hadrons} \quad . \qquad (46b)$$

They calculate 10^{-36} cm^2 for a 4 GeV/c^2 mass lepton at $E_{c.m.} = 30$ GeV. This cross section increases to 5×10^{-34} cm^2 at $E_{c.m.} = 300$ GeV. More generally they give a crude scaling law. For the region

$$m_L^2 \Big/ E_{c.m.}^2 \rightarrow 0 \qquad (46c)$$

$$\sigma \sim 10^{-34} \, \ell n\left(S \big/ E_{c.m.}^2\right) \text{cm}^2 \qquad (46d)$$

Those cross sections are 10^{-8} of the total pp cross section; hence the severe background problem for searches.

2) Lepton production through heavy hadron decay: Consider a very heavy hadron H produced in a p + p or $\bar{p}$ + p collision. Such a hadron might decay purely leptonically

$$H \rightarrow L + \nu_L \quad , \qquad (47a)$$

or semileptonically

$$H \rightarrow L + \nu_L + \text{hadrons} \quad . \qquad (47b)$$

These are weak decays and would be equally useful for charged leptons or neutral leptons. This mechanism has been extensively studied with respect to the τ neutrino and is discussed in Sec. VII.C.

B. Searches In Charged Particle Beams

The simplest type of search is to carefully study the nature of the charged particle beam produced by the primary proton beam hitting a fixed target. Such searches are always done when a new, higher energy, proton accelerator begins operation. Unfortunately no new particles have been found; indeed there have not even been any published reports of hints of new particles found this way. I'll note two examples.

1) Cronin et al.,[45] used 300 GeV protons on a Cu target, and looked for long-lived, penetrating, unit charge particles in the mass range of 1.0-6.8 GeV/c^2 at 2.4 GeV/c transverse momentum. No such particle was found compared to a yield of about 10^9 pions.

2) Bussiere et al.,[46] used 200-240 GeV/c protons on Be and Al targets to look for particles produced at 0° in the mass range of about 1-8 GeV/c^2. The charge was allowed to be $\pm 2/3$, ± 1, $\pm 4/3$ and ± 2. No new particles were found at a level about 10^{-11} of known particle production.

C. Proton Beam Dump Experiments

The beam dump search concept, Sec. VI.B and Fig. 11, is suitable for primary proton beams. The object is to look for stable or long-lived neutral leptons. This search method is illustrated by proposals[47-49] to directly detect the τ neutrino, ν_τ. The proposals are to use

$$p + N \rightarrow F^- + \text{hadrons} \tag{48a}$$

$$F^- \rightarrow \tau^- + \bar{\nu}_\tau \tag{48b}$$

$$\tau^- \rightarrow \nu_\tau + \text{charged particles} \tag{48c}$$

Here F is the charmed meson. The neutrinos from π and K decay would overwhelm the ν_τ signal unless the majority of the π's and K's interact before they decay. Therefore the entire proton beam must be dumped in a thick target, Fig. 11. There is still some problem with the prompt ν_e's and ν_μ's from D meson and other charmed particle semileptonic decays; but the detection of the ν_τ appears feasible, either through direct bubble chamber measurement of the track of the τ^- in

$$\nu_\tau + N \rightarrow \tau^- + \text{hadrons} \tag{49}$$

or through detection of a large missing transverse momentum when the τ in Eq. 49 decays.

Experiments using ν_τ beams so produced become easier as the primary proton beam energy increases. Therefore a number of proposals[50] have been made to the Fermi National Laboratory to do ν_τ experiments using the 1000 GeV Tevatron proton beam. Some of the current lower energy neutrino beam dump experiments at Fermilab[51] and CERN[52] may be able to detect ν_τ events.

The detection of a new neutral lepton, L^o, in a proton beam dump experiment involves considerations analogous to the detection of the ν_τ. The two fundamental requirements are a sufficiently copious production process in the beam dump, and a way to detect the L^o and to distinguish it from the ν_e, ν_μ and ν_τ. Shrock[53] has discussed the use of precise timing to isolate the L^o.

Turning now to the present experimental situation, I will comment on two sets of experiments.

1) Beam dump experiment at the BNL AGS: Soukes et al.,[54] used the 28.5 GeV primarily proton beam of the AGS to search for new penetrating neutral particles. An electronic detector was used. They find an excess of 48 neutrino-like events over the number of such events expected from conventional sources. The statistical and systematic errors are ±10 and ±12, respectively. A bubble chamber experiment[55] using the same beam dump did not find the excess, and another electronic experiment[56] sheds no light on the validity of these excess events. The situation has been reviewed by LoSecco[57] and by Dydak.[58] Incidently, these relatively low energy beam dump searches have the advantage over higher energy searches that there is negligible prompt neutrino background from charm particle decays. The disadvantage is, of course, the smaller mass range for the search.

2) Beam dump experiments at the CERN SPS: A beam dump experiment[52,58] has been carried out at the CERN SPS using 400 GeV protons. The beam dump was viewed simultaneously by two electronic neutrino detectors, those of the CHARM and CDHS collaboration,

and by the neon-hydrogen filled bubble chamber, BEBC. The primary purpose of this experiment was to measure the prompt neutrinos from charm particle decay in the target, and thus measure hadron-hadron production of charm particles. As you know, the measurements of some of the detectors show possible anomalies in the $\bar{\nu}_\mu/\nu_\mu$ and the ν_e/ν_μ flux ratios; although by and large the prompt neutrino flux is as expected. These possible anomalies have been studied with respect to neutrino mixing or neutrino oscillation theories, but that is not the subject of this review. I will make just two obvious and certainly unoriginal comments:

a) If the ν_e flux is indeed below the ν_μ flux, it could be due to the ν_e mixing with a hitherto unknown neutral lepton.

b) The CHARM collaboration[59] has reported an excess of low visable energy, muonless, events in their detector. Such an excess, if substantiated, could be an indicator of a new neutral lepton.

A new beam dump experiment is being planned at CERN to continue these studies with reduced systematic and statistical errors.

Before leaving the subject of proton beam dump searches, I note the search carried out by Bechis et al.,[60] at Fermilab. They used the concept in Fig. 11b and looked for neutral leptons with lifetimes in the 10^{-8} to 10^{-10} sec range. They found nothing, the search being most sensitive to masses below 1 GeV/c^2.

D. Searches Using pp and $\bar{p}p$ Colliding Beams

The proton-proton and antiproton-proton colliding beams machines now being constructed will provide $E_{c.m.}$ of 550 to 2000 GeV. Hence, lepton searches in the mass range of several hundred GeV are in principle possible. Two production mechanisma, the Drell-Yan process and massive hadron decay, have been described in Sec. A. There is now a third mechanism, the decays of the intermediate bosons

$$\begin{aligned} Z^o &\rightarrow L + \bar{L} \\ W^{\pm} &\rightarrow L^{\pm} + L^o \end{aligned} \tag{50}$$

The overwhelming problem, which will take time and ingenuity to solve, is how to find any new leptons produced at those colliders.

VIII. LEPTON SEARCHES IN MACROSCOPIC MATTER

It is possible that macroscopic matter contains charged, stable leptons which have evaded accelerator searches. The searches could fail because the lepton is too massive, or because there is no suitable production mechanism. We consider two possibilities: fractional charge and unit charge.

1) Stable, fractional charge, leptons in matter: Many quark searches in macroscopic matter use techniques which would equally well find fractionally charged leptons. This has been recognized by many investigators. For example, Fairbank and his colleagues[61] refer to their findings as concerning fractional charge rather than quarks. I will not discuss quark searches here because they are being reviewed by Susinno[62] at this conference. Reviews have also been written by

Jones[63] and by Lyons.[64] If the existence[61] of fractional charge in matter is confirmed, the next questions will be: is the charge from a quark or from a lepton.

2) Stable, unit charge, leptons in matter: There have been several searches[65-68] for heavy stable particles in matter. Such particles might be leptons. I will describe the most recent and most sensitive search by Smith and Bennett.[67]

Consider a positive, unit charge, heavy, stable particle which forms a hydrogen-like atom (with an electron) called X. In terrestrial water the molecule HXO might form through the action of cosmic rays. Smith and Bennett used electrolysis of heavy water to produce water samples which would contain the HXO concentrated. These samples were then studied with a mass spectrometer. They set the following upper limits on the concentration of X atoms in natural water, C_X

$$6\ m_p < m_X < 100\ m_p: \quad C_X \leq 2 \times 10^{-22}$$

$$100\ m_p < m_X < 350\ m_p: \quad C_X \leq 10^{-21}$$

Here m_X is the mass of the X, and m_p is the proton mass. These are remarkably sensitive limits.

IX. ACKNOWLEDGMENTS

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Table II. Lower Limits on the Masses of New Charged Sequential Leptons and Spin-0 Leptons from PETRA Experiments

Lower Limit on Mass (in GeV/c^2) with 95% Confidence		Collaboration				
		CELLO	JADE	MARK J	PLUTO	TASSO
Sequential			18.0	16.	14.5	15.5
Spin-0	e-type	16.4			13.	
	μ-type			15.		
References		26	9	10	11, 27	12

Table IIIA. Upper limits with 90% Confidence on $R(e^+e^- \rightarrow e^{*+}e^{*-})$ Assuming the e^* Decay Process is Completely $e^* \rightarrow e + \gamma$

Mass of e^* (GeV/c^2)	Upper Limit on R
0.5 - 0.6	0.0014
0.6 - 0.8	0.0027
0.8 - 1.0	0.0023
1.0 - 1.3	0.0025
1.3 - 2.0	0.0041
2.0 - 2.3	0.0030
2.3 - 2.5	0.0051
2.5 - 3.0	0.0096
3.0 - 3.2	0.0031
3.2 - 3.3	0.0110

Table IIIB. Upper limits with 90% Confidence on $R(e^+e^- \rightarrow \mu^+\mu^-)$ Assuming the μ^* Decay Process is Completely $\mu^* \rightarrow \mu + \gamma$

Mass of μ^* (GeV/c^2)	Upper Limit on R
0.6 - 1.6	0.0010
1.6 - 2.1	0.0014
2.1 - 2.5	0.0025
2.5 - 2.9	0.0043
2.9 - 3.2	0.0090
3.2 - 3.3	0.0193