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THE SEARCH FOR NEUTRAL LEPTONS*

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Searches for new neutral leptons are reviewed. Some models for proposed neutral leptons are described. Methods used in past, present, and future searches are described. The limits obtained by some completed searches are given.

I. INTRODUCTION

At present we know of three kinds of neutral leptons: the electron neutrino, the muon neutrino, and the tau neutrino. This paper reviews the search for additional neutral leptons. The method and significance of a search depends upon the model used for the neutral lepton being sought. Section II describes some models for the properties and decay modes of proposed neutral leptons. Past and present searches are reviewed in Sec. III. The limits obtained by some completed searches are given, and the methods of searches in progress are described. Future searches are discussed in Sec. IV.

II. MODELS FOR PROPERTIES AND DECAY MODES OF NEUTRAL LEPTONS

A. WITHIN THE STANDARD MODEL

1. No Mixing. In the standard model, the simplest case is a fourth generation

$$\begin{pmatrix} L^0 \\ L^- \end{pmatrix}_L \quad ; \qquad L^0_R,\ L^-_R \tag{1}$$

with no mixing between lepton generations. Using m for mass, if

$$m_{L^-} > m_{L^0} \tag{2}$$

the L^0 is stable. If $m_{L^-} < m_{L^0}$ then

$$m_{L^0} - m_{L^-} > m_W \tag{3a}$$

or

$$m_{L^0} - m_{L^-} < m_W \tag{3b}$$

Then the L^0 decays via the weak charged current thru a physical W, Eq. 3a and Fig. 1a, or thru a virtual W, Eq. 3b and Fig. 1b.

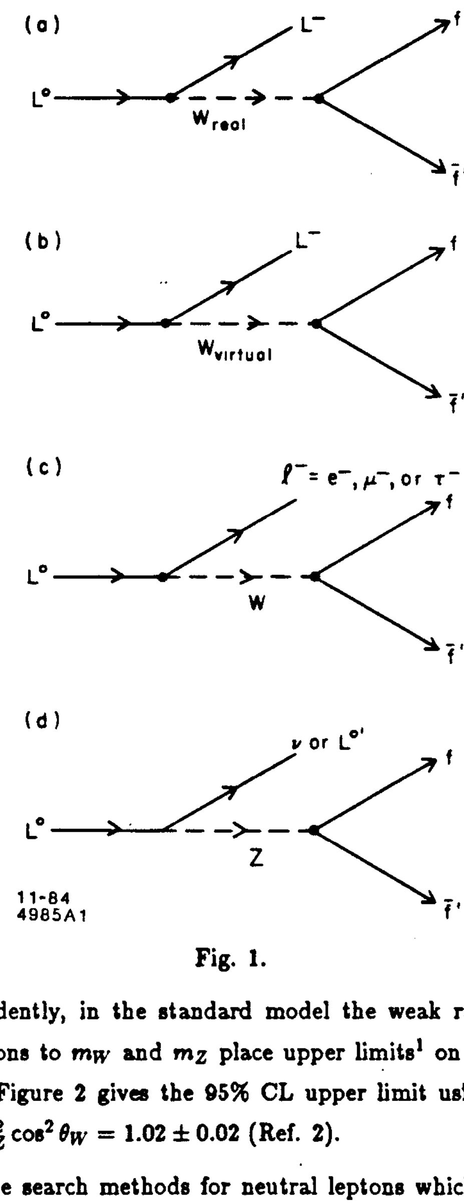

Fig. 1.

Incidently, in the standard model the weak radiative corrections to m_W and m_Z place upper limits[1] on $|m_{L^0} - m_{L^-}|$. Figure 2 gives the 95% CL upper limit using $\rho = M_W^2/M_Z^2 \cos^2\theta_W = 1.02 \pm 0.02$ (Ref. 2).

Some search methods for neutral leptons which decay via the weak charged current use the decay modes in which there are two charged particles, with or without neutrinos but without photons. This branching fraction, B_2, is given in Fig. 3.

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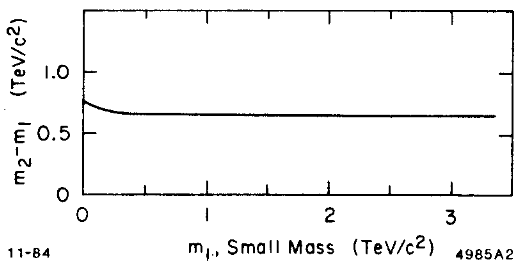

Fig. 2. Upper limits on $|m_{L^0} - m_{L^-}|$ from weak radiative corrections to W and Z masses.

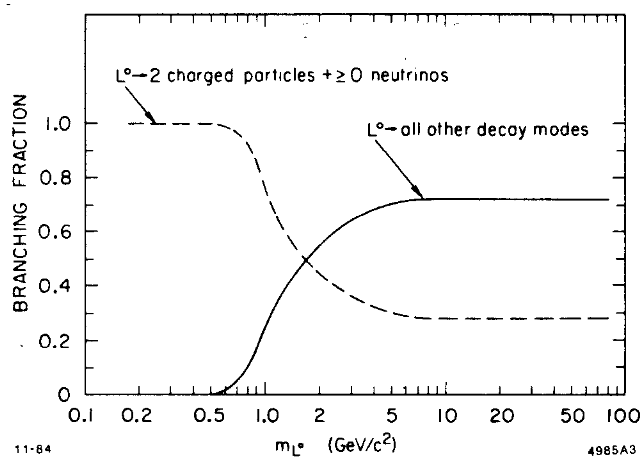

Fig. 3. Some branching fractions for the decay of an L^0 via the weak charged current, $L^0 \to \ell^- + X$. The ℓ^- mass is set to zero.

2. Mixing. There have been many discussions[3,4] of the possibility that a fourth generation lepton doublet might mix with one of the known lepton doublets

$$\begin{pmatrix} L^0 \cos\phi - \nu \sin\phi \\ L^- \end{pmatrix}_L \quad ; \quad L^0_R,\ L^-_R$$
$$\begin{pmatrix} L^0 \sin\phi + \nu \cos\phi \\ \ell^- \end{pmatrix}_L \quad ; \quad \ell^-_R \qquad (4)$$

Here $\ell = e$, μ, or τ. The decay diagram is Fig. 1c, and the decay amplitude is multiplied by $\sin\phi$. Photonic decays, Fig. 4, can also occur, but their decay rates are much smaller[5] than that described in Fig. 1c. The one γ decay rate is usually smaller than the two γ decay rate.

B. Deviations from the Standard Model

1. Flavor–Changing Neutral Current Decays. An interesting class of models allows decays thru a flavor–changing neutral current. In one example,[4] there is mixing between

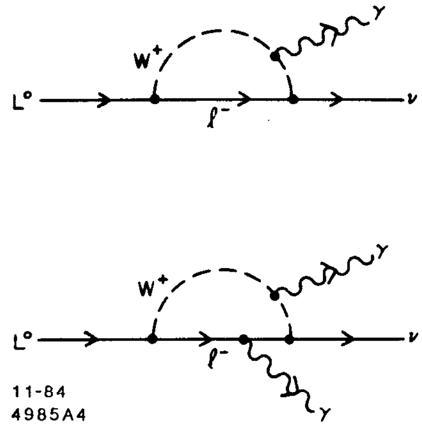

Fig. 4.

a weak isospin singlet neutral lepton

$$L^0 \cos\phi - \nu \sin\phi \qquad (5a)$$

and a known doublet

$$\begin{pmatrix} L^0 \sin\phi + \nu \cos\phi \\ \ell^- \end{pmatrix} \qquad (5b)$$

Now there is no GIM mechanism and the decay shown in Fig. 1d will occur. Another example assumes a pair of neutral leptons L^0, $L^{0\prime}$ with a unique conserved lepton number, and $m_{L^0} > m_{L^{0\prime}}$. Then, Fig. 1d,

$$L^0 \to L^{0\prime} + \text{neutral current decay modes} \qquad (6)$$

To model these neutral current decays we violate the standard model, we assume $V - A$ coupling and assume decay thru a virtual or real Z^0. Figure 5 gives some branching fractions.

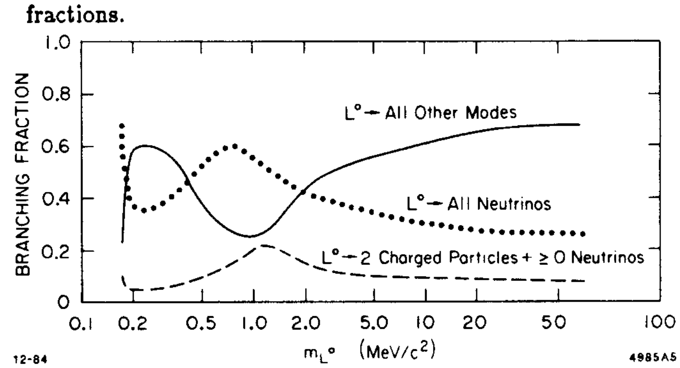

Fig. 5. Some branching fractions for the hypothetical decay via a weak neutral current, $L^0 \to L^{0\prime} + X$. The $L^{0\prime}$ mass is set to zero.

2. Other Deviations from the Standard Model. Out of the many other deviations from the standard model which have been proposed, I'll give two examples. A heavy neutral lepton may be assigned the same lepton number as a known charged lepton,[6,7] an E^0 associated with the e^-, or an M^0 associated with the μ^-. The decay proceeds via a charged current which might be right-handed.

Another example consists of an L^0, L^- pair with unconventionally strong coupling to a Higgs particle. Then the decay could be dominated by the process in Fig. 6.

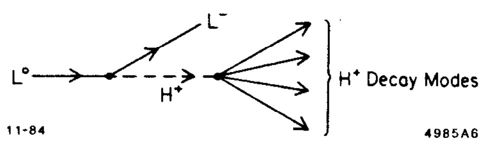

Fig. 6.

Fishbane et al.,[8] give other examples which fit into a generalized standard model.

C. Models and Decay Signatures

Many past, present, and future searches depend upon looking for special decay signatures. Table I gives an overview of decay signatures based on some of the models we have discussed.

III. PAST AND PRESENT SEARCHES

A. Searches Using μ, π, or K Decay

If a new neutral lepton, L^0, mixes with the e or μ and has sufficiently small mass, it might be detected in decays such as

$$\mu^- \to L^0 + e^- + \bar{\nu}_e$$

$$\pi^- \to L^0 + \mu^- \qquad (7)$$

$$K^- \to L^0 + \mu^-$$

Two methods are used as illustrated by the work of D. A. Bryman et al.,[9]

They studied the decay

$$\pi^+ \to e^+ + \text{any neutral lepton} \qquad (8)$$

in the course of measuring the decay rate for the conventional process $\pi^+ \to e^+ + \nu_e$. The first search method involves looking for a peak in the e^+ energy spectrum corresponding to a non-zero mass L^0. None was found, Fig. 7a and curve A in Fig. 7b give 90% CL upper limits. The second search method involves the measurement of the ratio.

Table I

Model	Decay Signatures	Remarks
$\begin{pmatrix} L^0 \\ L^- \end{pmatrix}$; $m_{L^0} - m_{L^-} > m_W$	$L^0 \to L^- + W^+$	W decays + new L^-
$\begin{pmatrix} L^0 \\ L^- \end{pmatrix}$; $m_{L^0} - m_{L^-} < m_W$	$L^0 \to L^- + \nu_\ell + \ell^+$	2 charged particles
	$L^0 \to L^- + q + \bar{q}'$	Large multiplicity
$\begin{pmatrix} L^0 \\ L^- \end{pmatrix}$ mixing with $\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}$	$L^0 \to \ell^- + \nu' + \ell'^+$	2 charged particles
	$L^0 \to \ell^- + q + \bar{q}'$	Large multiplicity
$\begin{pmatrix} L^0 \\ L^{0\prime} \end{pmatrix}$ with flavor changing neutral current	$L^0 \to L^{0\prime} + \nu + \bar{\nu}$	All neutral particles
	$L^0 \to L^{0\prime} + \ell^+ + \ell^-$	2 charged particles
	$L^0 \to L^{0\prime} + q + \bar{q}'$	Large multiplicity
L^0 stable	None	

$$\Gamma(\pi^+ \rightarrow e^+\nu_e)/\Gamma(\pi^+ \rightarrow \mu^+\nu_\mu) \qquad (9)$$

This ratio will be greater than expected if there is an L^0 with near-zero mass such that the decay $\pi^+ \rightarrow e^+ + L^0$ gives the same e energy spectrum as $\pi^+ \rightarrow e^+ + \nu_e$. Curve B in Fig. 7b gives the upper limit from this method.

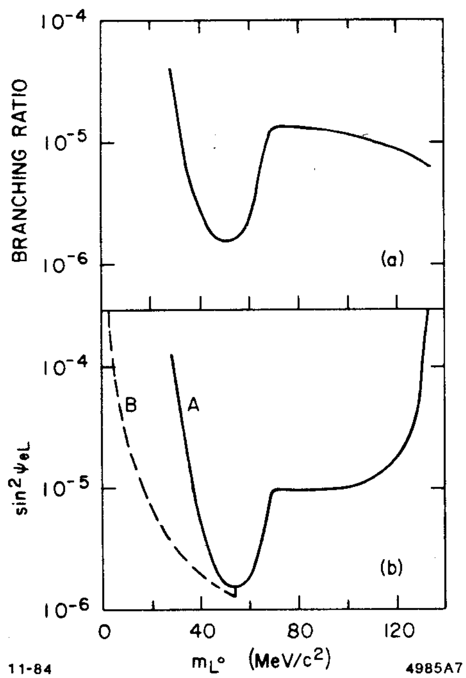

Fig. 7. Upper limits on branching ratio and $\sin^2\,\phi_{eL}$.

Shrock[10] summarizes many of the searches which have used μ, π, or K decays. All gave null results. Figure 8, abstracted from that summary gives some of the upper limits.

B. Searches Using Neutrino Beams and Beam Dumps.

A new neutral lepton might be detected via a study of the neutrino-like products of a beam dump experiment, Figs. 9a and 9b, or via a study of the contents of a neutrino beam produced by meson decay, Fig. 9c.

1. Neutrino Beam Dump Searches. Beam dump experiments consist of the interaction of a high intensity proton or electron beam with a dense target, the removal within a short distance of almost all strongly-interacting or electromagnetically-interacting particles by a dense shield, and magnetic sweeping from the forward direction of muons. Most π's and K's interact before decay, hence the dominant

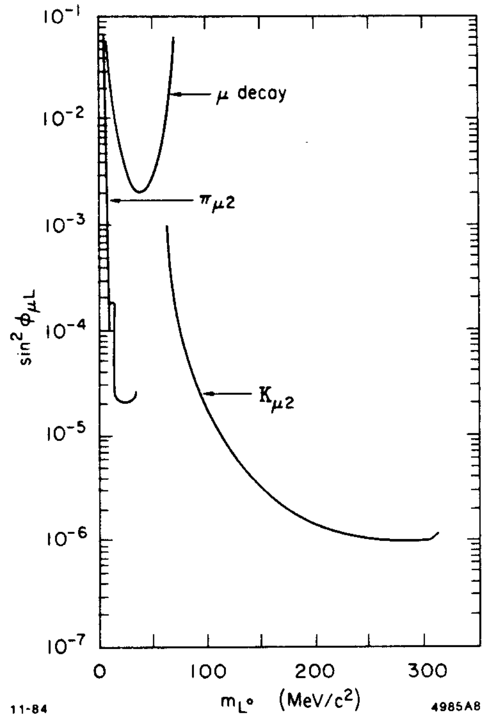

Fig. 8. Upper limits on $\sin^2\,\phi_{\mu L}$.

products of the beam dump are neutrinos from D, B, or τ decay. Unknown weakly-interacting neutral particles from these latter decays would also exit the beam dump.

Figures 9a and 9b illustrate two search methods: looking for an unexpected interaction in a massive neutrino detector, or looking for decays in flight.

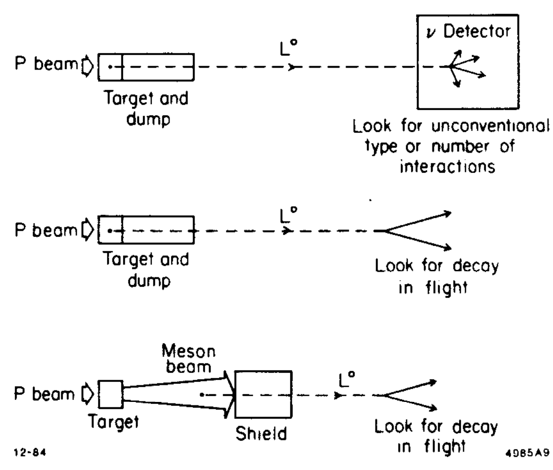

Fig. 9.

In recent years a series of proton beam dump experiments have been carried out at the CERN SPS[11] and a single experiment was carried out at Fermilab[12]. No definite evidence was found for non-conventional processes in the beam dumps or in the detectors. But there is lack of agreement on whether the ratio of ν_e flux to ν_μ flux is conventional. If the dominant production mechanism is D and other charmed particle decays, then $e-\mu$ universality predicts a ratio close to 1. The CHARM experiment[11] reports a smaller ratio. If there is indeed such an effect, could it be connected to the existence of a unknown L^0? Rosner[13] has discussed possible extensions of beam dump searches.

The CHARM experiment has also looked for decays in flight[11,14] via the processes

$$D^+ \rightarrow e^+ + L^0 \qquad \text{(in beam dump target)}$$

$$L^0 \rightarrow \nu_e + e^+ + e^- \qquad \text{(downstream of beam dump)} \tag{10}$$

Figure 10 gives the upper limits.

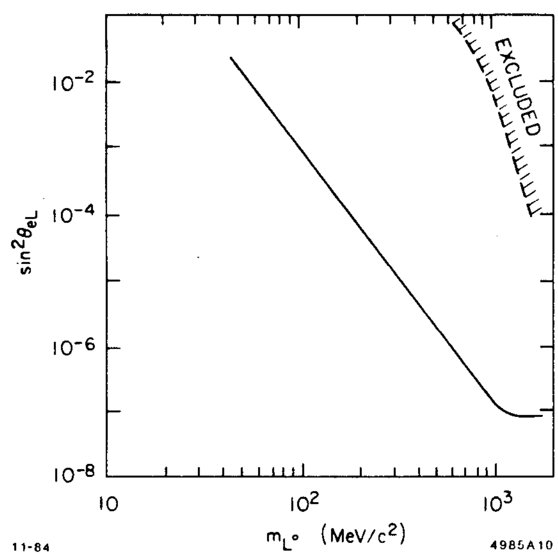

Fig. 10 Upper limits on $\sin^2\phi_{eL}$.

Bjorken et al.,[15] have used an electron beam dump experiment at SLAC to look for axion-like bosons, photons, and other neutral, penetrating particles.

2. Neutrino Beam Searches. The CHARM experiment[14] has also used the CERN wide band neutrino beam to search for the processes

$$\pi^+ \rightarrow e^+ \text{ or } \mu^+ + L^0$$
$$K^+ \rightarrow e^+ \text{ or } \mu^+ + L^0 \tag{11a}$$

and then

$$L^0 \rightarrow \nu_e \text{ or } \nu_\mu + e^+ + e^- \tag{11b}$$

as in Fig. 9c. Upper limits are given in Fig. 11 for 90% CL.

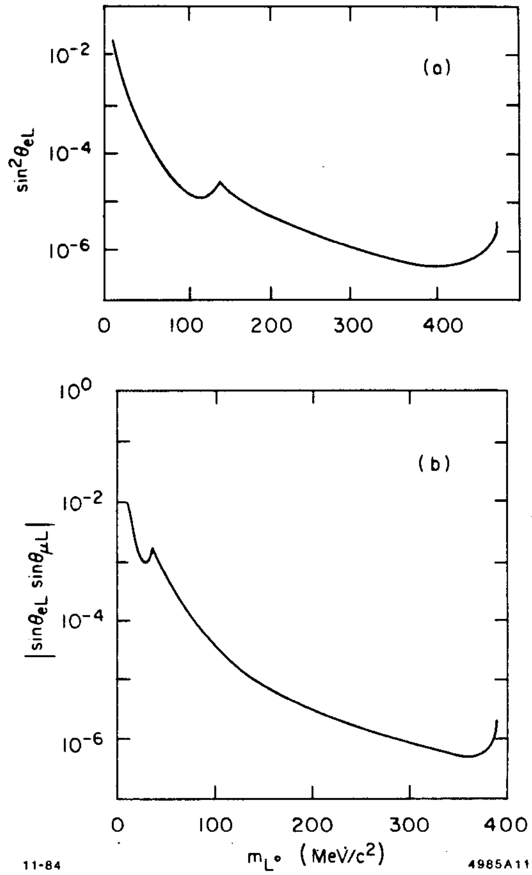

Fig. 11. Upper limits.

C. Searches Using e^+e^- Interactions

1. General Search Methods. The process

$$e^+ + e^- \rightarrow L^0 + \bar{L}^0 \ , \tag{12}$$

as shown in Fig. 12, provides a general production method.

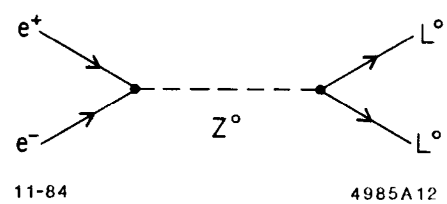

Fig. 12.

If L^0 does not fit within the standard model, we may not know the production cross section. However, it is useful to define as a standard the cross section in the standard model

$$\sigma_{\text{standard}} = (G^2 s/96\pi)(a_e^2 + v_e^2)(a_{L^0}^2 + v_{L^0}^2)T(\beta) \tag{13a}$$

In the standard model the threshold factor is

$$T(\beta) = \beta(3 + \beta^2/4) \tag{13b}$$

where β is the velocity of the L^0 in units of c. The number of produced pairs per 100 pb^{-1} is

$$\text{PEP } (29\ GeV): \quad \text{pairs}/100\ pb^{-1} = 30.T(\beta)$$
$$\text{PETRA } (42\ GeV): \quad \text{pairs}/100\ pb^{-1} = 59.T(\beta) \qquad (14)$$

At present most PEP experiments have accumulated about 200 pb^{-1} of data, most PETRA experiments about 100 pb^{-1}. Hence each PEP or PETRA experiment could have about 60 $T(\beta)$ produced pairs. However, the reality of L^0 searches in existing detectors is that acceptances are roughly 10% to 40% when the various cuts are applied. Hence each PEP or PETRA experiment could have about 6 $T(\beta)$ to 25 $T(\beta)$ observed $L^0\bar{L}^0$ pairs summed overall decay modes. This is a small signal in a background of 10^4 hadronic events.

The search for new neutral leptons in PEP and PETRA data is still going on because the sought signals are so small. I will review some of the search methods being used and, where available, the limits set by some searches.

2. Searches Depending on Mixing. If an L^0 mixes with one of the known lepton doublets and decays through the weak charged current,[16] then

$$e^+ + e^- \to L^0 + \bar{L}^0$$
$$L^0 \to \ell^- + \text{other particles} \qquad (15)$$
$$\bar{L}^0 \to \ell^+ + \text{other particles}$$

where $\ell = e,\ \mu$, or τ. In the e or μ case the signature will be definitive.

The HRS-collaboration[17] has applied this method to 106 pb^{-1} of PEP data using the signature

$$L^0 \to e^{\pm} + x^{\mp} + \geq 0\ \nu's \qquad (16a)$$
$$\bar{L}^0 \to \text{anything} \qquad (16b)$$

They find a few events with this signature, but the expected background is also a few events. Their 90% CL upper limit is

$$B_2\sigma < 0.08 \text{ to } 0.20\ pb \qquad (17)$$

in the mass range of $1-7\ GeV/c^2$, where B_2 is the branching fraction for the decay in Eq. 16a. From Fig. 3 and Eq. 13a we expect $B_2\sigma \sim 0.1\ pb$ in the standard model.

The HRS collaboration is extending this search, and other searches involving mixing are being carried out by the Mark II collaboration, the MAC collaboration and other PEP and PETRA experiments.

3. Searches Using Decay Secondary Vertices. Figure 13 gives the lifetime of neutral leptons decaying thru the charged weak interaction

$$L^0 \to \ell^- + \text{anything} \qquad (18)$$

in the standard model. The ℓ^- mass is neglected. Existing detectors at PETRA and PEP can look for secondary decay vertices over a range of masses and mixing parameters.

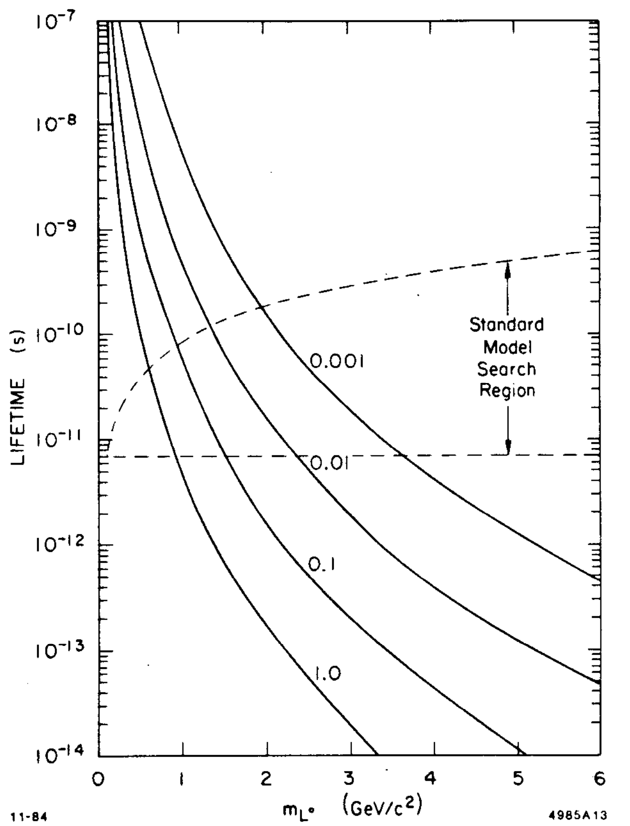

Fig. 13. Lifetime for the decay $L^0 \to \ell^- +$ anything through the weak charged current. The curves are for the indicated values of $\sin^2\phi$.

Using the Mark II as an example, the minimum lifetime is set by how well a secondary vertex can be distinguished from the $L^0\bar{L}^0$ production vertex on an <u>event by event</u> basis. The rough rule is

$$cT \gtrsim 0.2\ cm$$

where T is the L^0 lifetime. Hence

$$T \gtrsim 7 \times 10^{-12} sec. \qquad (19a)$$

The maximum lifetime is set by the need for the L^0 to decay within the inner regions of the detector, hence

$$\gamma c T \lesssim 50\ cm$$

The total energy of 29 GeV at PEP yields

$$T \lesssim 10^{-10}\ M\ sec. \qquad (19b)$$

where M is the L^0 mass in GeV/c^2. The search region given by Eq. 19 is indicated in Fig. 13. Within the standard model, this region has definite significance. Outside the standard model, for example

$$L^0 \to \nu + \text{anything}\ , \qquad (20)$$

the significance of the search region depends upon the model.

The Mark II Collaboration is testing various L^0 models by searching for decay secondary vertices in the following types of events: 2-prongs versus missing momentum, 4-prongs, 2-prongs versus jet, and jet versus jet. This work is in progress. The HRS Collaboration[18] and other collaborations are carrying out similar searches.

4. Searches Using Small Multiplicity Events. If the L^0 has a mass of the order of 1 GeV/c^2 or smaller and decays through the weak charged current, then the dominant decay modes contain two charged particles:

$$L^0 \to a^+ + b^-$$
$$L^0 \to c^+ + d^- + \nu \qquad (21)$$

as shown in Fig. 3. Here the letters represent an e, μ, π or K. Therefore it is interesting to search for small mass unstable neutral leptons in the four charged particle reaction

$$e^+ + e^- \to a^+ + b^- + c^+ + d^- + \geq 0 \text{ neutrinos} \qquad (22)$$

Such a search has just been completed by the Mark II Collaboration.[19] The major background is from τ pairs where there is a 1-prong decay opposite a 3-prong decay. This background is eliminated by requiring that no combinations of three particles has a small invariant mass. Another powerful criterion, which greatly reduces background from $e^+e^- \to e^+e^+e^+e^-$, $e^+e^-\mu^+\mu^-$, requires

$$E_{a^+} + E_{b^-} \leq E_{\rm beam},\ E_{c^+} + E_{d^-} \leq E_{\rm beam} \qquad (23)$$

for at least one combination of a, b, c, d. Here E_i is the energy of particle i assuming zero mass. No events were found in the mass range

$$0.1 < m_{L^0} < 6\ GeV/c^2 \qquad (24)$$

consistent with $e^+ + e^- \to L^0 + \bar{L}^0$ and the decay modes in Eq. 21. The 0.1 lower limit is a criterion used to eliminate e^+e^- pairs. Figure 14 gives the 90% CL upper limit on $\sigma/\sigma_{\rm standard}$ (see Eq. 13a).

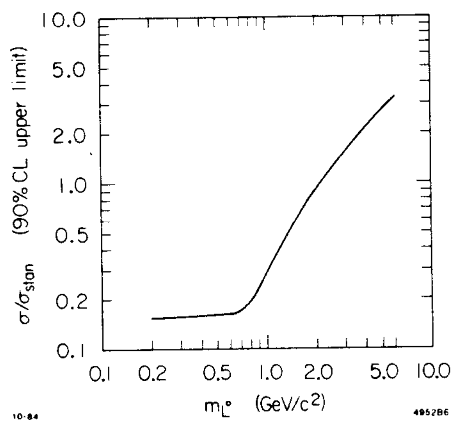

Fig. 14. The 90% CL upper limit on $\sigma/\sigma_{\rm standard}$ for $e^+e^- \to L^0\bar{L}^0$ yielding 4 charged particle events.

5. Special Searches in e^+e^- Interactions. The JADE Collaboration[20] at PETRA has looked for the e^--associated E^0 lepton produced as in Fig. 15. The 95% CL lower limits on m^0_E are 24.5 GeV/c^2 assuming $V + A$ and 22.5 GeV/c^2 assuming $V - A$, and based on the model in Ref. 20.

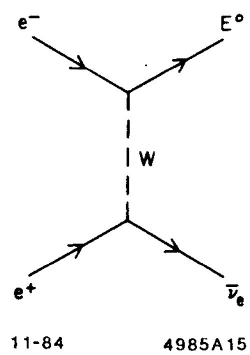

Fig. 15.

4. Present Experimental Limits on the Number of Different Neutral Leptons

Direct or indirect measurements of the Z^0 width can provide upper limits to the number of different neutral lepton decay modes

$$Z^0 \to L^0 + \bar{L}^0 \quad (25)$$

assuming m_{L^0} is sufficiently small so that threshold effects can be ignored. Table II gives the current limits on the total number of small mass L^0's. The small upper limit given by the UA2 measurement of the ratio $\sigma(\bar{p}p \to ZX)/\sigma(\bar{p}p \to ZX)$ may be caused by their $\sigma(\bar{p}p \to ZX)$ being anomalously large.

Table II

Method	Number of Small Mass L^0's 90% CL Upper limit	Ref.
Z width $< 6.2\ GeV$ UA2, 90% CL	24	21
Z width $< 8.5\ GeV$ UA1, 90% CL	37	22
$\sigma(\bar{p}p \to ZX)/(\sigma(\bar{p}p \to WX)$ UA2	3	21
$\sigma(\bar{p}p \to ZX)/(\sigma(\bar{p}p \to WX)$ UA1	18	23

IV FUTURE SEARCHES

A. Non-Collider Searches

Searches for L^0's will certainly continue using the methods described in Secs. IIIA and IIIB: studies of μ, π, K and D decays; beam dump searches; and neutrino beam searches. It is doubtful that there will be many future searches using the interactions of charged or neutral leptons with fixed targets. (Such searches are discussed in Ref. 6).

B. Searches Using e^+e^- Colliders

1. Energies Below and at the Z^0 Mass. The searches described in Sec. IIIc will continue at PEP and PETRA. Increased instantaneous luminosity and increased total luminosity will improve the sensitivity of these searches.

The next steps will use the higher energy e^+e^- colliders, TRISTAN, LEP, and the SLC. As the energy increases towards the Z^0, the standard model production cross section, Eq. 13a, increases as the energy squared. Equally important is the increase of the mass range.

At the peak of the Z^0 resonance, which is in the LEP and SLC energy range, the search for L^0's is definitive[24] provided $m_{L^0} < m_Z/2$. The standard model cross section for

$$e^+ + e^- \to Z^0_{\rm real} \to L^0 + \bar{L}^0 \quad (26)$$

is approximately 2 nb, ignoring threshold factors. LEP and SLC will attain luminosities in the range of 10^{30} – $10^{31}\ cm^{-2}s^{-1}$ at the Z^0. Hence 2×10^4 to 2×10^5 L^0 pairs could be produced per year. If the L^0 is unstable, signatures such as those summarized in Table I will enable[24] the discovery and study of the L^0.

If the L^0 is stable or unstable, the Z^0 width will be larger than expected (Sec. IIID), and a precise width measurement can be undertaken.[25] An alternate method[26] requires the collider energy to be set above the Z^0 peak, looking for the reaction

$$e^+ + e^- \to \gamma + Z^0 \to \gamma + L^0 + \bar{L}^0 \quad (27)$$

This method seems to be the easier of the two.

2. Energies above the Z^0 Resonance. At energies above the Z^0 resonance, the standard model cross section for

$$e^+ + e^- \to Z^0_{\rm virtual} \to L^0 + \bar{L}^0 \quad (28)$$

is

$$\sigma \sim 0.03/s\ pb \quad (29)$$

where s is in TeV^2 and threshold effects are ignored. The higher energy phase of LEP is designed to reach $\sqrt{s} = 0.2$ to 0.25 TeV. There are no e^+e^- colliders under construction which can reach higher energy. At present it seems necessary to use the linear collider technology,[27,28,24] to reach e^+e^- energies in the range of $\sqrt{s} = 0.5$ to 4 TeV. In this very high energy range one might find lepton doublets with

$$m_{L^0} - m_{L^-} > m_W \tag{30a}$$

$$L^0 \rightarrow L^- + W \tag{30b}$$

Then Eq. 28 would yield

$$e^+ + e^- \rightarrow L^0 + \bar{L}^0 \rightarrow L^+ + L^- + W^+ + W^-, \tag{31}$$

a reaction with a distinctive signature. The decay in Eq. 30b has the width[29]

$$\Gamma = \frac{Gm_L^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_{L^0}}\right)^2 \left(1 + \frac{2m_W^2}{m_{L^0}}\right) \tag{32a}$$

where the L^- mass has been ignored and a standard gauge coupling assumed. For $m_{L^0} \gg m_W$,

$$\Gamma \approx G_F m_L^3 / 8\pi\sqrt{2} \approx 3 \times 10^{-7} m_L^3 \; GeV \tag{32b}$$

where m_{L^0} is in GeV. Thus for very heavy leptons the decay width can be the same magnitude as the mass. Of course the limitations associated with Fig. 2 apply to $m_{L^0} - m_{L^-}$ in the standard model.

C. Searches Using ep Colliders

HERA, the ep collider[30,31] now under construction, offers a wonderful way to search for neutral leptons via

$$e^- + p \rightarrow E^0 + \text{hadrons} \tag{33}$$

The cross section can be large[31] and the signature is distinctive, the E^0 decay products and the hadrons exit the reaction in different directions. HERA can produce L^0's with masses up to about 200 GeV. If pp or $p\bar{p}$ colliders in the 10 to 40 TeV range are built, e^- rings can be added, and the E^0 search extended to the TeV mass range.

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

1. Production and Search Methods. The general L^0 production mechanism is the decay of real or virtual W's or Z's, these bosons having been produced through quark-antiquark annihilation:

$$\begin{gathered} p + p \text{ or } \bar{p} \rightarrow q + \bar{q}' + x \\ q + \bar{q}' \rightarrow W^- \text{ or } Z^0 \\ W^- \rightarrow L^- + \bar{L}^0 \text{ or } Z^0 \rightarrow L^0 + \bar{L}^0 \end{gathered} \tag{34}$$

Discussions now in the literature[32–35] have concentrated on

$$W^-_{\text{real}} \rightarrow L^- + \bar{L}^0 \,, \tag{35}$$

and emphasized the search for the L^- while assuming the L^0 is stable and has small mass. In this case the signature for the process in Eq. 35 is the L^- decay products and missing momentum, which is not a general signature for an L^0 search.

However the decay in Eq. 35 can have some useful signatures depending on the model used for the L^- and L^0 and their masses. For example, if the L^0 is massive, unstable, and decays to the L^-

$$\begin{aligned} &W^- \rightarrow L^- + L^+ + \ell^- + \bar{\nu}_e \,, \qquad \ell = e,\ \mu,\ \tau \\ &W^- \rightarrow L^- + L^+ + q + \bar{q}' \,, \qquad q = \text{quark} \end{aligned} \tag{36}$$

The threshold factor for the W^- decay is given in Fig. 16. Even when $m_{L^-} + m_{L^0}$ is close to m_W, the threshold factor is greater than 0.2. Hence a large mass range can be explored.

The other real boson decay process is

$$Z^0_{\text{real}} \rightarrow L^0 + \bar{L}^0 \tag{37}$$

The signature considerations are analogous to those discussed in connection with Eq. 26, the background considerations are, of course, very different, the background being larger in the pp or $\bar{p}$ case.

The L^0 production processes involving virtual W's or Z's require more complicated search procedures since the constraint of the boson mass is not available.

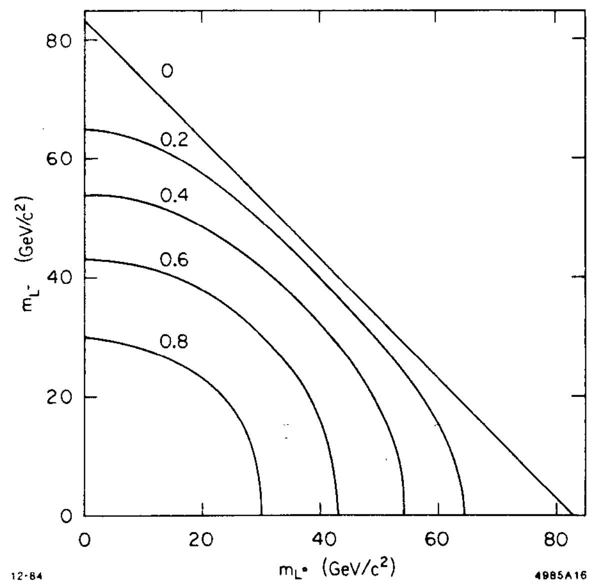

Fig. 16 The threshold factor in $W^- \to L^- + \bar{L}^0$.

2. Searches at the CERN $\bar{p}p$ Collider and Tevatron I. Searches for new leptons are just beginning at the CERN $\bar{p}p$ Collider. The search range will certainly extend up to the W or Z mass, perhaps higher. When the Tevatron I $\bar{p}p$ collider begins operation, the search range will extend to several hundred GeV mass. Only experiment and experience will tell us if there is an L^0 in these mass ranges which can be detected and shown to be a lepton.

At present some events found by the UA1 Collaboration[36] have the form

$$\bar{p} + p \to \text{jet} + \text{large missing transverse energy} \qquad (38)$$

The missing energy might be explained by a long lived L^0 or an L^0 which decays into neutrinos, hence there have been some proposals[37] that these events came from Z^0 decay into new neutral leptons. It is clearly just the beginning of the large amount of research which will be done on neutral leptons at $\bar{p}p$ colliders.

3. Searches at Ultra-high Energy pp and $\bar{p}p$ Colliders. Research and development work on pp and $\bar{p}p$ colliders in the 10 to 40 TeV range has begun in the United States[38] and in Western Europe.[39,40] The reaction

$$\begin{aligned} p + p &\to W^\pm + \text{anything} \\ W^\pm &\to L^\pm + L^0 \end{aligned} \qquad (39)$$

has been studied.[2] Figure 17 gives the $L^\pm$ production cross section assuming the L^0 has negligible mass. The cross seciton would be similiar if the L^0 were massive and the L^- had negligible mass.

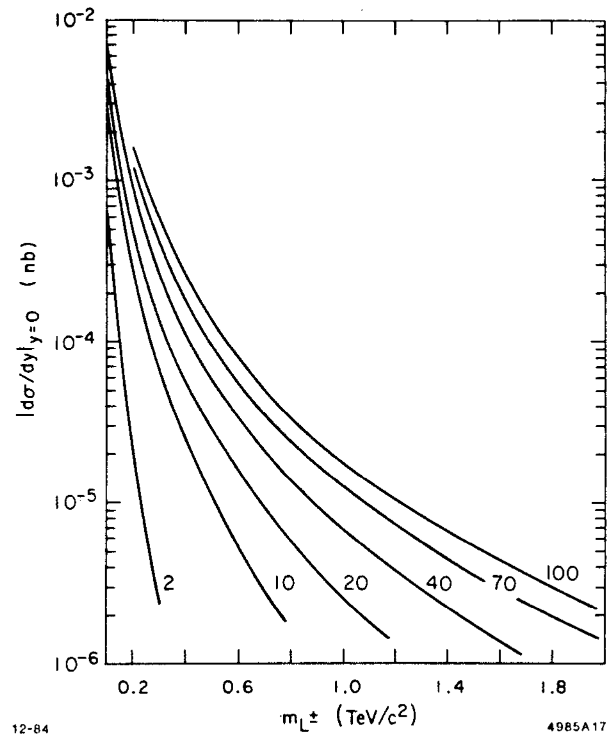

Fig. 17. The cross section for $p+p \to L^\pm + L^0 +$ anything via W_{virtual} production.

Of particular interest is the application of Fig. 17 to the proposed Superconducting Super Collider,[41] a pp collider of up to 40 TeV total energy. The L^0 search range extends into the 1 TeV mass range.

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