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SEARCHES FOR HEAVY LEPTONS AND ANOMALOUS LEPTONIC BEHAVIOR — THE PAST AND THE FUTURE*

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I. INTRODUCTION

In this report to the Seminar on the μ-e Problem I have undertaken two tasks. First, I will summarize the results of some past searches for heavy leptons and for the anomalous behavior of leptons. Second, I shall describe some of the searches for these phenomena which are planned in the next few years. I must apologize for two very large areas of concern to this Seminar which I will omit. In describing the future searches I shall mostly restrict myself to the work being planned in the United States. For talking about the future is always an uncertain business, and it becomes more uncertain, the further one wanders from home. Therefore I will not discuss most of the experimental work in this field which is being carried out in the Soviet Union or in Europe. The second area of omission lies in the theoretical province. In order to concentrate my efforts on experimental work and experimental plans, I shall say very little about theoretical considerations and I shall make very few references to theoretical papers.

As I am sure most of you know, there is no definitive evidence for the existence of heavy leptons or for anomalous leptonic behavior. Therefore the purpose of this paper is to separate those areas of research where one might fruitfully seek these phenomena from those areas which have been fully explored. And further, I hope to indicate which unexplored areas might, in my view, be most profitably pursued. To this end, I shall not hesitate to be speculative.

The plan of the paper is as follows. Some possible types of heavy leptons are classified in Section II, and the predicted decay properties of the heavy leptons are summarized in Section III. In Sections IV and V I discuss heavy lepton searches. In discussing each of the search methods I shall follow the following sequence. First the method itself is described, then the results of past searches are summarized, and finally some future searches using this method are listed. In the final section of the paper, Section VI, I discuss some of the types of anomalous leptonic behavior which have been conjectured; and I shall describe the results of searches or tests for such anomalous behavior. In a brief Appendix the units and the meaning of some abbreviations used in this paper are given.

This paper is based on papers published and preprints circulated before June, 1972.

II. SOME POSSIBLE TYPES OF HEAVY LEPTONS

To simplify the discussion of past and future searches for heavy leptons, I shall consider four experimental classes of these hypothetical particles. The first three classes are defined according to the leptonic number properties of the leptons.

A. Heavy Sequential Leptons: $\mu', \mu'' \ldots$

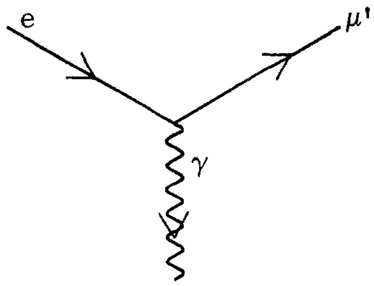
Suppose heavy leptons exist in the mass sequence

$$e, \mu, \mu', \mu'' \ldots \quad , \tag{1}$$

with associated neutrinos

$$\nu_e, \nu_\mu, \nu_{\mu'}, \nu_{\mu''} \ldots \quad . \tag{2}$$

Further suppose that each charged lepton and its associated neutrino possess a unique lepton number property which is different from the lepton number possessed by every other charged lepton-neutrino pair, and that these lepton numbers $(n_{\mu'})$ are separately conserved in strong, electromagnetic and weak interactions. In particular there are no electromagnetic vertexes of the form



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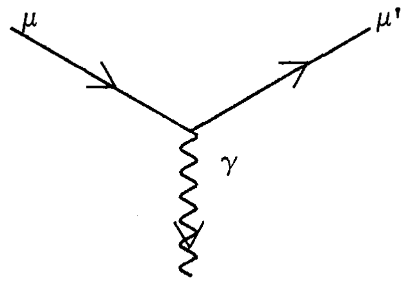


;

and the charged heavy sequential leptons cannot decay electromagnetically. I refer to the charged leptons or their associated neutrinos as <u>heavy sequential leptons</u> and use the respective symbols μ' and $\nu_{\mu'}$. The use of the term sequential emphasizes that the properties of these heavy leptons follow in the main sequence of the e and the μ. In particular, I assume that the mass of the associated neutrino is zero. And following the e and μ conventions, the lepton number $n_{\mu'}=+1$ is associated with the μ'^- and $\nu_{\mu'}$. In writing reactions I shall generally use the μ'^- as an example and for brevity omit the corresponding μ'^+ reaction.

B. <u>Heavy Excited Leptons: e*, μ*</u>

Suppose there exists a heavy charged lepton which possesses the same lepton number property as the electron, or the muon, of the same sign of charge. Then the electromagnetic couplings just pictured are allowed, and the electromagnetic decays

$$e^{*\pm} \rightarrow e^{\pm} + \gamma\ , \qquad \mu^{*\pm} \rightarrow \mu^{\pm} + \gamma \tag{3}$$

occur. As was pointed out by Low[1] and discussed in more detail by Barut <u>et al.</u>,[2] the simplest form for the electromagnetic coupling of the e to the e* (or the μ to the μ*) which obeys current conservation is

$$e\left(\frac{\lambda}{M^*}\right)\left[\sigma_{\mu\nu} F^{\mu\nu} + \text{h.c.}\right] \ . \tag{4}$$

λ is an unknown dimensionless constant which measures the relative strength of this special electromagnetic interaction compared to the conventional electromagnetic interaction. The mass of the heavy excited lepton, M*, is inserted simply to make λ dimensionless. It is convenient, and perhaps stimulating to the imagination, to think of the e* and μ* as the respective excited states of the e and μ. Hence I designate the e* and μ* by the term heavy excited lepton. We may also consider the existence of a neutral heavy excited lepton, namely the heavy neutrino, ν*, with the same lepton number as is possessed by the ν_e or the ν_μ. However we shall not require that the e* and ν*, or the μ* and ν*, occur in pairs. In discussing the heavy excited charged leptons, I shall generally use the e* as the example.

C. Special Pairs of Heavy Leptons

Lipmanov[3] and others[4-8] have suggested that a lepton, say the e', might have the same lepton number as the e of the opposite electric charge. The lepton number scheme would be

$$\begin{aligned} &e^-, \nu_e, e'^+, \bar{\nu}_{e'} \quad \text{have} \quad n=+1 \quad , \\ &e^+, \bar{\nu}_e, e'^-, \nu_{e'} \quad \text{have} \quad n=-1 \quad . \end{aligned} \tag{5}$$

A special case of this hypothesis is the assumption that the μ and the e form such a pair,[6-10] namely

$$\begin{aligned} &e^-, \nu_e, \mu^+, \bar{\nu}_\mu \quad \text{have} \quad n=+1 \quad , \\ &e^+, \bar{\nu}_e, \mu^-, \nu_\mu \quad \text{have} \quad n=-1 \quad . \end{aligned} \tag{6}$$

D. Stable and Very Long Lived Heavy Leptons

One may always assume that there is a special conservation rule or a special set of circumstances which give a heavy lepton a very long life or allow it to be stable.[11-13] Such special conditions are necessary to prohibit the decay processes which lead to the short lifetimes discussed in the next section. A simple way to obtain a stable heavy charged lepton is to assume that the lepton has a unique lepton number as in case of heavy sequential leptons, but to also assume that the associated neutrino has a nonzero mass which is greater than the mass of the charged lepton.

E. Other Possibilities

Obviously there are yet other possibilities for new types of heavy leptons, both charged and neutral.[14] I have emphasized the four types described in II.A through II.D because they are convenient experimental classes upon which the discussion of the searches can be based.

F. A Word on Notation

As an aid to the memory I shall use the notation μ', μ'' ... to denote a heavy sequential lepton, I shall use e^* and μ^* to denote heavy excited leptons, and I shall use the script ℓ to denote any type of heavy lepton.

III. THE DECAY PROPERTIES OF THE HEAVY LEPTONS

A. Charged Heavy Sequential Leptons

The charged heavy sequential lepton will decay, through the weak interactions, in the leptonic modes

$$\mu'^- \rightarrow \nu_{\mu'} + e^- + \bar{\nu}_e \quad , \tag{7}$$

$$\mu'^- \rightarrow \nu_{\mu'} + \mu^- + \bar{\nu}_\mu \quad ; \tag{8}$$

and, depending on the μ' mass, in the hadronic modes

$$\mu'^- \rightarrow \nu_{\mu'} + \pi^- \quad , \tag{9}$$

$$\mu'^- \rightarrow \nu_{\mu'} + K^- \quad , \tag{10}$$

and

$$\mu'^- \rightarrow \nu_{\mu'} + 2 \text{ or more hadrons} \qquad (11)$$

The decay rates (Γ) for the leptonic modes, Eqs. (7) and (8), have been discussed by many authors.[15-21] The calculation is straightforward if conventional, first order, weak interaction theory is used. I remind the reader that for

$$M_{\mu'} >> M_{\mu}$$

$$\Gamma(\mu'^- \rightarrow \nu_{\mu'} + \mu^- + \bar{\nu}_{\mu}) \approx \Gamma(\mu'^- \rightarrow \nu_{\mu'} + e^- + \bar{\nu}_e) = \frac{G^2 M_{\mu'}^5}{192\,\pi^3} \qquad (12)$$

where

$$G = 1.02 \times 10^{-5}/M_p^2 \qquad (13)$$

and M_p is the mass of the proton.

However, we should keep in mind that the leptonic decay processes of heavy leptons of large mass may not obey conventional, first order, weak interaction theory. In these decay processes there are four-momentum transfers between the leptons whose maximum value is

$$|q^2|_{max} \approx M_{\mu'}^2 \quad . \qquad (14)$$

We know very little about weak interactions when $|q^2|$ is greater than 1 or 2 $(GeV/c)^2$. Therefore if $M_{\mu'} >> 1$ GeV/c^2, Eq. (12) may not be applicable. Thus the discovery of heavy leptons of large mass will not only be tremendously important in itself, but the leptonic decay processes of these particles will be very interesting to study.

The calculations of the hadronic decay processes, Eqs. (9), (10), and (11), are more difficult and uncertain; and assumptions about the specific leptonic coupling of the hadrons must be introduced. I refer the reader to Refs. 15-21 for the details, and turn the reader's attention to Fig. 1 where the calculations of Tsai[15] are used.

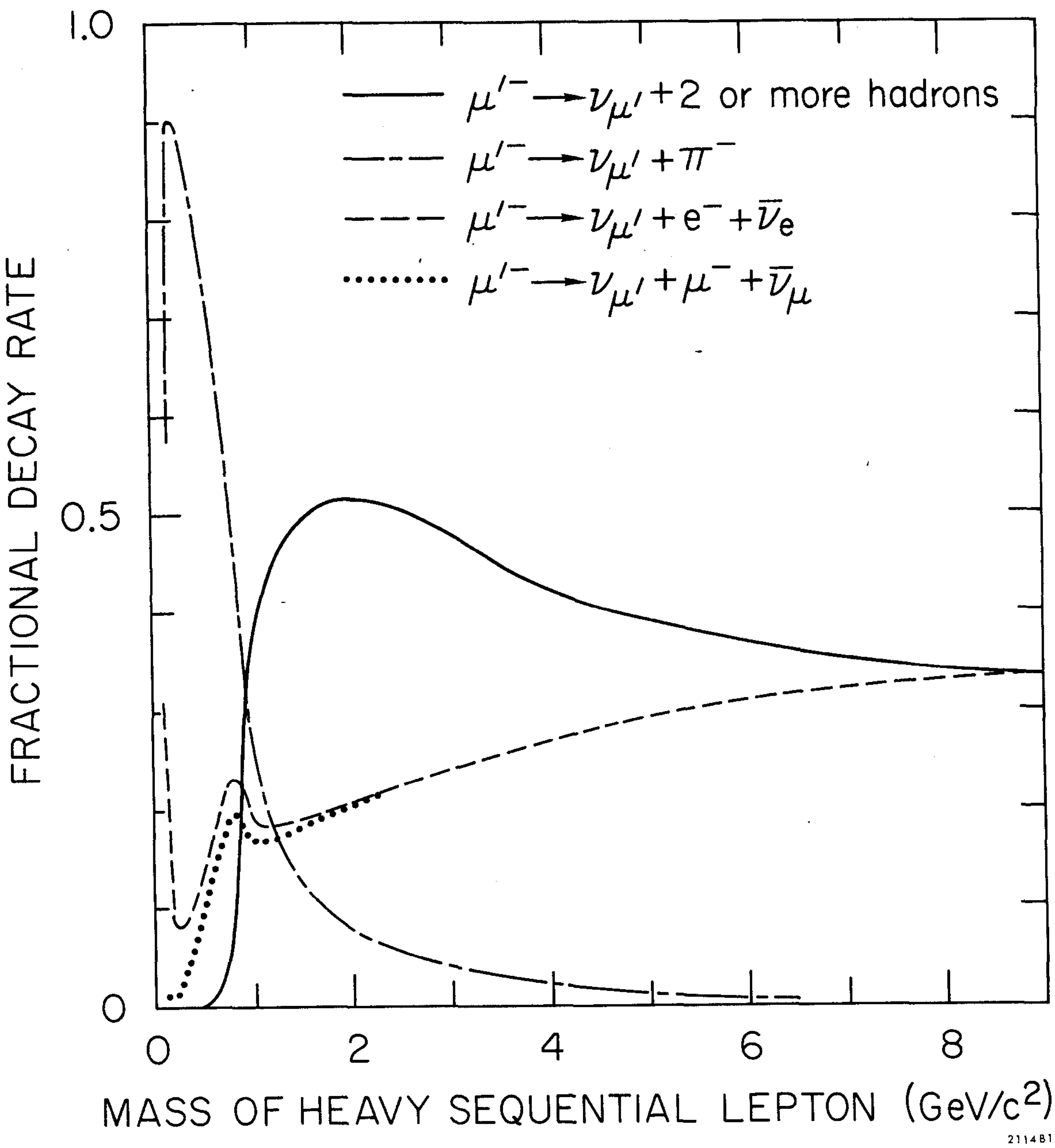


FIG. 1--Fractional decay rates of heavy sequential leptons based on calculations discussed in the text.

of Tsai[15] are used. For $M_{\mu'}$ in the vicinity of .5 GeV/c^2, the decay process $\mu'^- \rightarrow \nu_{\mu'} + \pi^-$ dominates. But for $M_{\mu'}$ above 1 GeV/c^2, the leptonic decay modes and the 2 or more hadrons decay mode, Eq. (11), dominate.

The decay rate for the 2 or more hadrons decay mode is of course the most difficult to predict from first principles. Therefore only crude estimates, based on very general ideas can be made for this mode. For example, Tsai,[15] Thacker and Sakurai,[20] and others have used the conserved vector current hypothesis to relate the rate of this mode, $\Gamma(\mu'^- \rightarrow \nu_{\mu'}$ + 2 or more hadrons), to the total cross section for electron-positron <u>annihilation</u> into hadrons, $\sigma(e^+ + e^- \rightarrow$ hadrons). Of course $\sigma(e^+ + e^- \rightarrow$ hadrons) is at present only known[22] up to a hadronic invariant mass of about 2 GeV, and even then the measurement is very rough. Using these measurements and the crude approximation that $\sigma(e^+ + e^- \rightarrow$ hadrons) behaves with energy like the cross section for the production of two point particles, Tsai[15] obtains, for sufficiently large $M_{\mu'}$, the simple result

$$\begin{aligned} \Gamma(\mu'^- \rightarrow \nu_{\mu'} + 2 \text{ or more hadrons}) &\approx \Gamma(\mu'^- \rightarrow \nu_{\mu'} + e^- + \bar{\nu}_e) \\ &\approx \Gamma(\mu'^- \rightarrow \nu_{\mu'} + \mu^- + \bar{\nu}_\mu) \quad . \end{aligned} \tag{15}$$

This result can also be obtained by a model in which a parton-antiparton pair is formed in the μ' decay, the pair then annihilating into hadrons. The process is

$$\begin{aligned} &\mu' \rightarrow \nu_{\mu'} + \text{parton} + \text{antiparton} \\ &\text{parton} + \text{antiparton} \rightarrow \text{hadrons} \ . \end{aligned} \tag{16}$$

Here we must assume that the partons are point particles coupled by conventional, first order, weak interaction theory to the $\mu'^- \rightarrow \nu_{\mu'}$ current. To return to Fig. 1, we have used the approximate relationship of Eq. (15) to obtain the high mass end of the figure.

Thus we see that (1) for μ' masses extending from 1 GeV upward there is not much change, with the μ' mass, to be expected in the ratio of leptonic to hadronic decay modes, and (2) the heavy sequential lepton can be sought either through its leptonic or hadronic decay modes.

In this discussion I have ignored the possibility of the existence of an intermediate boson W which mediates the weak interactions. If the mass of this boson M_W is less than $M_{\mu'}$, the decay rate of the process

$$\mu'^{-} \rightarrow \nu_{\mu'} + W \tag{17}$$

will be much greater than the processes we have been considered. This is easily seen as follows. The decay rate for this process is[15]

$$\Gamma(\mu' \rightarrow \nu_{\mu'} + W) = GM^3_{\mu'} \left[\frac{(1-r^2)^2(1+2r)}{8\pi\sqrt{2}}\right] \tag{18}$$

where

$$r = \left(M^2_W/M^2_{\mu'}\right) < 1 \quad . \tag{19}$$

Comparison of Eq. (18) with Eq. (13) yields the approximate ratio

$$\frac{\Gamma(\mu'^{-} \rightarrow \nu_{\mu'} + W)}{\Gamma(\mu'^{-} \rightarrow \nu_{\mu'} + e^{-} + \bar{\nu}_e)} \sim \frac{1}{GM^2_{\mu'}} \sim 10^5 \quad . \tag{20}$$

Therefore if $M_W < M_{\mu'}$ the observed decay modes of the μ' will be just the decay modes of the W. Since the W is still a hypothetical particle, we can say little about the details of its hadronic modes. But we can apply to the W the same very general considerations which led to Eq. (15). Therefore we expect that the μ' and the W, if their masses are in the several GeV/c^2 range or larger, will have roughly similar 2 or more hadron decay modes and roughly similar ratios of that mode to the leptonic modes. Thus the search experiment that first finds the μ' will probably <u>not</u> show if the intermediate boson forms a step in the decay chain through the process of Eq. (17).

The lifetime of the μ' will of course depend upon whether or not there is an intermediate boson W with $M_W < M_{\mu'}$. In Fig. 2 we show the lifetime of the μ' assuming that there is <u>no</u> W with $M_W < M_{\mu'}$. If such a W exists, the μ' has the very short lifetime[15]

$$\tau \approx 2.5 \times 10^{-23} \left(\frac{M_p}{M_{\mu'}}\right)^3 \left[\frac{1}{(1-r^2)^2(1+2r)}\right] \text{ sec} \quad . \tag{21}$$

B. <u>Charged Heavy Excited Leptons</u>

The very dominant decay mode for the charged heavy excited leptons e* is

$$e^* \rightarrow e + \gamma \; ; \tag{22}$$

all other decay modes have ratios which are smaller by at least the factor α^2. The lifetime for $M_{e*} >> M_e$ is[23]

$$\tau = \frac{1}{\alpha M_{e*} \lambda^2} = \frac{.9 \times 10^{-22}}{M_{e*}\lambda^2} \text{ sec} \quad , \tag{23}$$

where M_{e*} is in GeV/c^2. From the viewpoint of the experimentalist searching for heavy excited leptons, the dominance of the decay process of Eq. (22) can be most unfortunate. This is because in some search methods, it is difficult to detect leptons which have decayed through Eq. (22). I will say more about this in the next section.

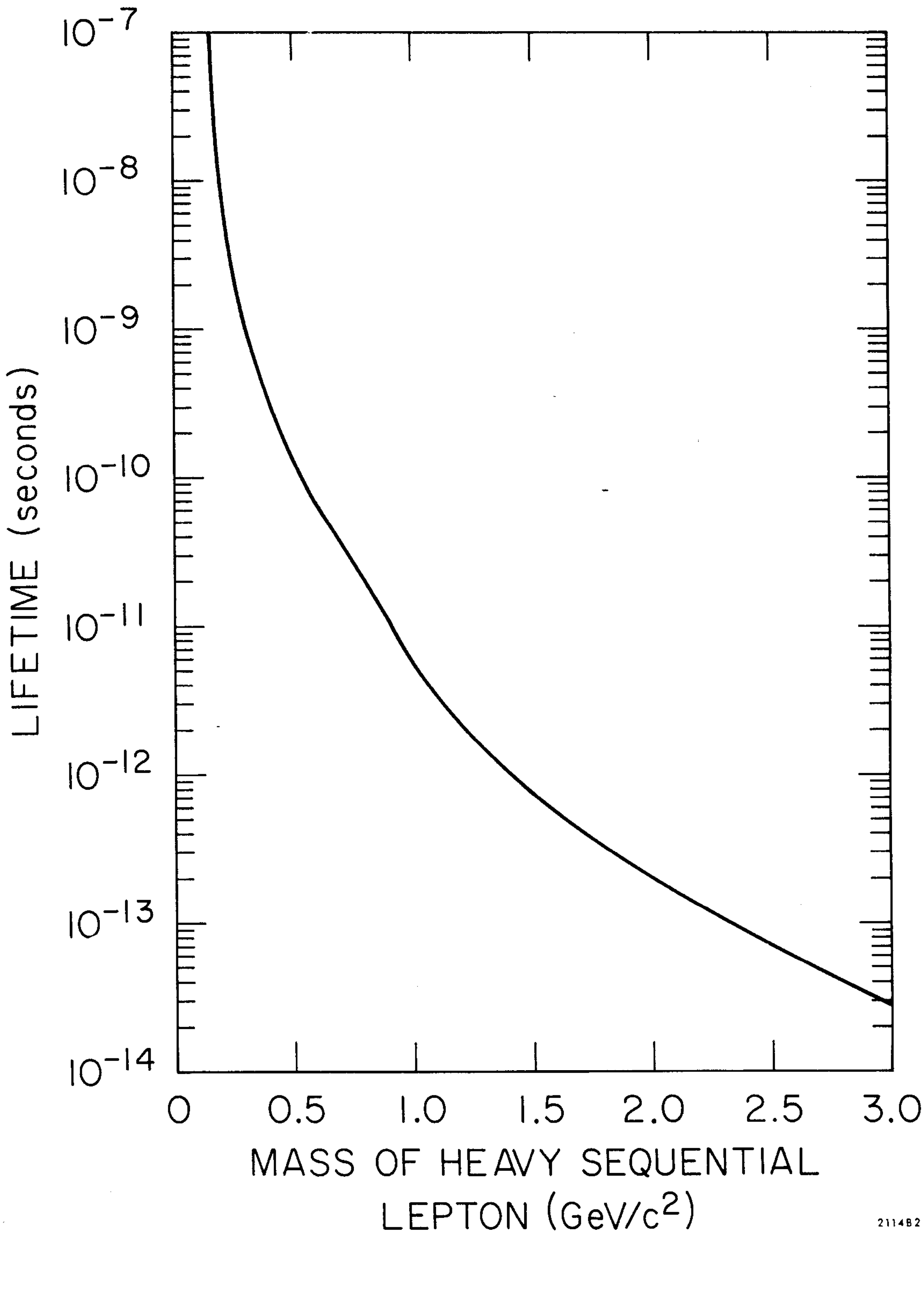


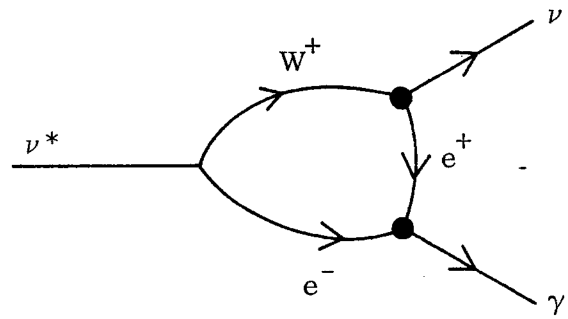
FIG. 2--Lifetime versus mass of heavy sequential leptons based on calculations discussed in the text.

C. <u>Neutral Heavy Excited Leptons</u>

The decay process for neutral heavy excited leptons, that is heavy neutrinos, are very dependent upon the theory one adopts for their existence and properties. For example, the decay

$$\nu^* \rightarrow \nu + \gamma \tag{24}$$

can take place through the diagram



if the intermediate boson W exists. This subject of the ν^* will be discussed by other speakers at this Seminar so that I need not discuss it here in detail. For the present I shall only make the obvious remark that decay modes such as that of Eq. (24) are most difficult to detect.

IV. SEARCHES FOR LOW MASS OR STABLE HEAVY LEPTONS

When the mass of the heavy lepton is sufficiently small, there are two convenient search methods. First, if the charged or neutral heavy lepton has a mass M_ℓ less than the pion mass M_π or kaon mass M_K, the heavy lepton ℓ can appear in the decay of the pion or kaon respectively. Second, for heavy sequential leptons, a small mass leads to a lifetime sufficiently long to permit detection of the lepton is a particle beam of conventional length — namely tens of meters.

A. Searches in the Decay Modes of the Pion and Kaon

1. The Method

Most past searches of this type have involved direct observation in a bubble chamber, but counters have been used.[24] Some recent tests of the Ramm effect[25] discussed below use wire spark chambers. There is no uniform method and the reader should consult the references which are cited in this section.

2. Past Searches

With one exception which will be discussed below, no evidence for heavy leptons, either charged or neutral has been found in the study of the decay modes of the pion or kaon. Rothe and Wolsky[21] summarized the situation in 1968. An earlier summary is provided by Beier,[24] who carried out a search for heavy sequential leptons with masses just below the kaon mass.

The exception to these null results is the work of Ramm[25] who reports evidence for a neutral heavy meson μ^{o*} the decay $K_L^o \rightarrow \mu^{\pm} + \pi^{+} + \nu_{\mu}$. The heavy lepton appears as a narrow resonance in the $\mu^{o*} \rightarrow \mu^{\pm}\pi^{\mp}$ mass spectrum with mass $.422 < M_{\mu\pi} < .437$ GeV/c^2. Ramm[25] also reports evidence in neutrino interactions and in muon bremsstrahlung[26,27] for a charged counterpart with the decay mode $\mu^* \rightarrow \mu^- + \gamma$. Unfortunately, this work has not been verified by other studies of the K_L^o decay spectrum. While most of these studies with null results have not been published, Clark et al.[28] have published a very high statistics study, also reporting a null result. The weight of all the evidence appears at present to be against the existence of the Ramm neutral heavy lepton. There is no published evidence, beyond that presented by Ramm,[25,27] for or against the existence of the Ramm charged heavy lepton. Therefore the confirmation or rejection of this particle must await further experiments, in particular a new measurement of the muon bremsstrahlung spectrum in the $(\mu\gamma)$ invariant mass range of .4 to .5 GeV/c^2 would be very useful.[29]

3. Future Searches

I know of no plans for further searches for heavy leptons in pion or kaon decay modes, except for searches associated with the question of the existence of the Ramm effect. However the latter are usually associated with other experiments.[29] See for example Section V.A.

B. Searches in Particle Beams for Short-Lived Charged Heavy Leptons

1. The Method

For a charged heavy lepton to be directly detected in a particle beam, the lepton's decay length in the laboratory frame must be of the order of magnitude of, or greater than, say 10 meters. This requires a laboratory decay time of at least 3×10^{-8} seconds. If the particle has a laboratory frame energy E_ℓ, the time dilation factor (E_ℓ/M_ℓ) may permit detection of particles with particle rest frame lifetimes (τ_ℓ) as short as (M_ℓ/E_ℓ) (3×10^{-8}) seconds.

Searches at electron accelerators are most useful because, as is discussed in Section V.B the heavy leptons are pair produced by photons with a known cross section, if they have unit charge. Searches at proton accelerators are less definitive, because the production cross section of the heavy leptons is not known; this production uncertainty is discussed in Section V.C.

2. Past Searches

Examples of searches at electron accelerators all with null results, are the experiment of Coward et al.[30] who searched in the mass range of .5 to 90 MeV/c^2, and the experiment of Barna et al.[12, 13] who studied the mass range[31] of .2 to 1.0 GeV/c^2. Because of their uncertain sensitivity, searches at proton accelerators are usually not reported, although we may be sure that any unknown charged particle which was found in a beam would have been reported. We can set a crude upper limit to the mass range of these searches by noting that at the older proton accelerators $(M_\ell/E_\ell) \gtrsim .01$. Therefore $\tau_\ell \gtrsim 3 \times 10^{-10}$ seconds and, from Fig. 2, $M_\ell \lesssim .35$ GeV/c^2.

In closing this section we note a recent experiment of Ansorge et al.[32] in which a search was made for charged and neutral particles with masses less than .1 GeV/c^2. The search method involved the study of electron pair production and electron-like bremsstrahlung in a hydrogen bubble chamber. No new particles were found.[32]

3. Future Searches

I know of no special plans for future direct searches for low mass, short-lived, heavy leptons. The problem is that the new higher energy accelerator do not enlarge substantially the mass range over which charged heavy sequential leptons can be directly found in particle beams. For example, increasing E_ℓ by a factor of 10 decreases the lower limit on τ_ℓ by a factor of 10. But since τ_ℓ decreases at least as fast as M_ℓ^{-5}, this only extends the upper limit on M_ℓ to $10^{1/5}$ (.35) = .56 GeV/c^2. Nevertheless I hope that experimenters who study the mass spectra of particle beams at Serpukov, NAL, or the CERN 300 GeV accelerator will look in these beams for low mass, short-lived, charged heavy leptons.

C. Searches for Stable Charged Heavy Leptons in Particle Beams

1. The Method

The only question with respect to this type of search is whether its sensitivity is sufficient. Assuming unit charge for the leptons, this sensitivity can be determined quite well for particle beams produced by electrons or photons, Section V.B; but for beams produced by protons, the more uncertain considerations of Section V.C must be used to determine the sensitivity.

2. Past Searches

No stable heavy leptons have been found. At electron accelerators the search has been conducted[12, 13] with sufficient sensitivity up to a heavy lepton mass of 1.0 GeV. References 33-35 are examples of searches at proton accelerators. An analysis of some of these searches by Gerstein et al.,[11] using the method described in Section V.C, concludes that no stable heavy leptons exist with masses lower than 2.0 GeV/c^2. I have not tried to independently confirm this conclusion.

3. Future Searches

I assume that everyone who is studying the spectra of particles produced at any of the new accelerators will search for stable heavy leptons. Gerstein et al.[11] have given an example of the sensitivity that can be achieved at the Serpukhov accelerator.

Finally I note that it is quite easy to look for stable charged heavy leptons at electron-positron colliding beam facilities. Such a search will be carried out at the SLAC facility, SPEAR, which is discussed in Section V.A.3.

V. SEARCHES FOR HEAVY LEPTONS WITH MASSES GREATER THAN ABOUT .5 GeV/c^2

In the last section I showed that the search for heavy leptons with masses less than .4 or .5 GeV/c^2 was just about complete. And I showed that no heavy leptons with masses less than .4 or .5 GeV/c^2 have been proven to exist.

Therefore the future of heavy lepton searches belongs to the mass range above .5 GeV/c^2. As discussed in Section III, heavy sequential leptons, and of course heavy excited leptons, above this mass will have lifetimes less than 10^{-9} or 10^{-10} seconds. These heavy leptons must therefore be detected through their decay products. How this has been done and will be done is the subject of this section.

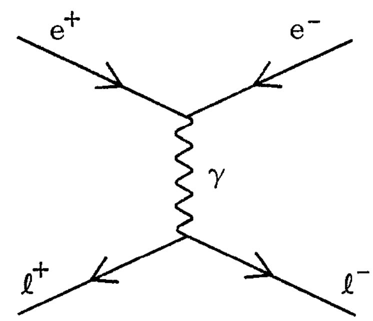
A. Electron-Positron Colliding Beams Production of Heavy Leptons

1. The Method

The production of charged heavy leptons pairs ℓ^-, ℓ^+ in electron-positron colliding beams takes place through the reaction

$$e^- + e^+ \rightarrow \ell^- + \ell^+ \tag{25}$$

The dominant Feynman diagram for this process is



Assuming the heavy leptons are Dirac point particles with unit charge, the total production cross section is

$$\sigma(e^-e^+ \rightarrow \ell^-\ell^+)(E) = \frac{\pi\alpha^2}{2E^2}\beta\,[1-\beta^2/3] \quad , \tag{26}$$

where E is the energy of either the electron or positron beam, and β is the velocity of the ℓ.

Given that the electron-positron colliding beams have sufficient energy for lepton production, $E > M_\ell$, this method provides in my view the best way to search for heavy leptons. This method has the following advantageous properties:

(a) The production cross section, Eq. (26), is relatively large. Once E is somewhat larger than M_ℓ, β approaches 1, and

$$\sigma(e^-e^+ \to \ell^-\ell^+) \approx \sigma(e^-e^+ \to \mu^-\mu^+) \approx \frac{2 \times 10^{-32}}{E^2} \text{ cm}^2 \quad , \tag{27}$$

where E is in GeV. Thus $\ell^-\ell^+$ pairs are produced almost as copiously as $\mu^-\mu^+$ pairs. Furthermore, measurements at ADONE[36] tend to indicate that the total production cross section for hadrons $\sigma(e^-e^+ \to \text{hadrons})$ is probably given by

$$\sigma(e^-e^+ \to \text{hadrons}) \approx \frac{3 \times 10^{-32}}{E^2} \text{ cm}^2 \tag{28}$$

in the few GeV range. Therefore the production of $\ell^-\ell^+$ pairs is about as copious as the production of hadrons. In fact, as pointed out by Sakurai,[19] a large part of the hadron production cross section could be due to the hadronic decay mode of undetected heavy sequential mesons which are being produced in the reaction of Eq. (25).

(b) This production cross section is relatively independent of the spin or electromagnetic moment properties of the ℓ. Higher spins, anomalous magnetic moments or higher electromagnetic moments usually increase $\sigma(e^-e^+ \to \ell^-\ell^+)$. This cross section will only be substantially smaller than that given in Eq. (26), if the electric charge of the ℓ is much less than that of the electron, or if the ℓ has a form factor which is much less than unity for $q^2 = 4E^2$.

(c) The heavy lepton production cross section, Fig. 3 rises quite rapidly once $E > M_\ell$. This helps to provide a clear test of the existence of the ℓ, since

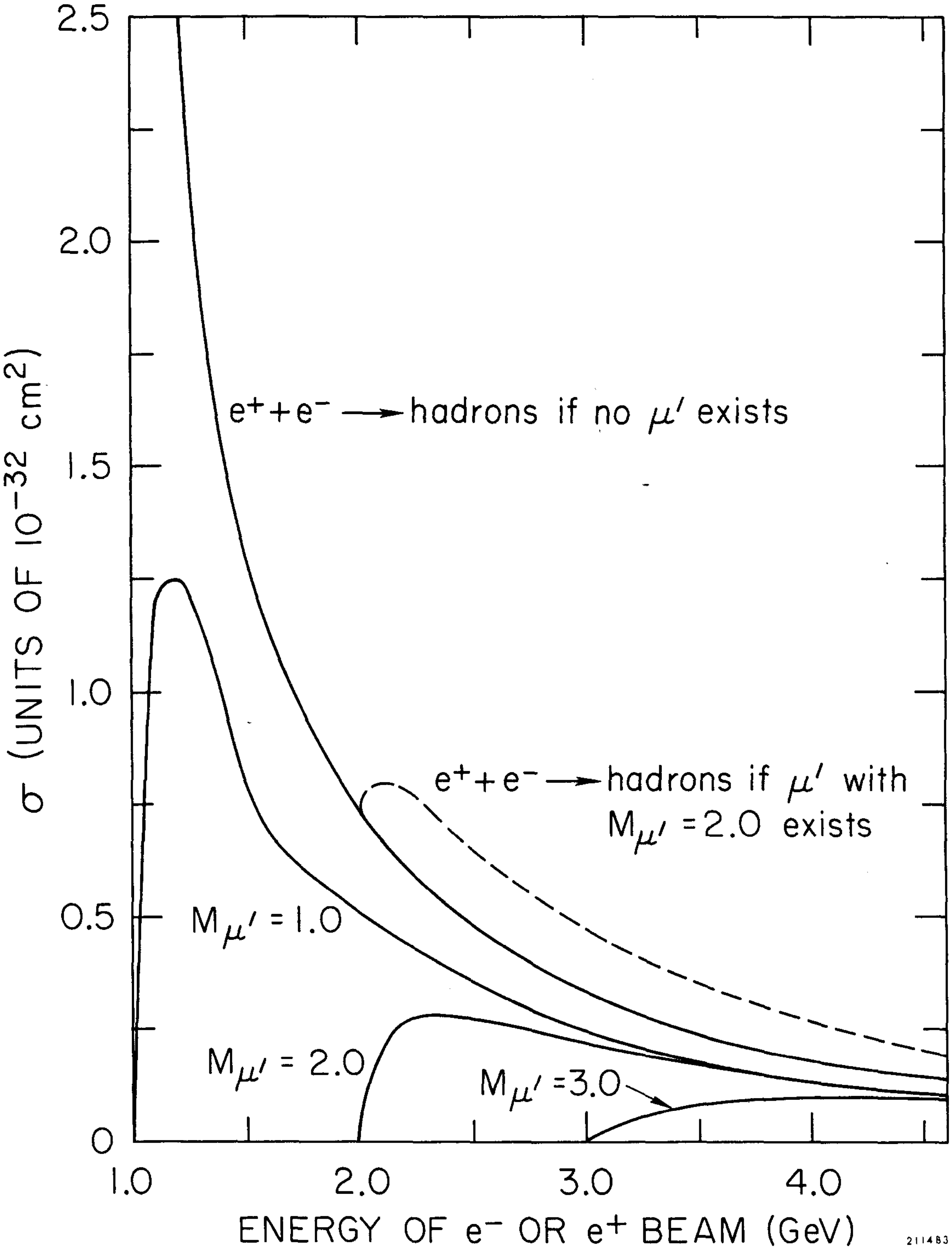


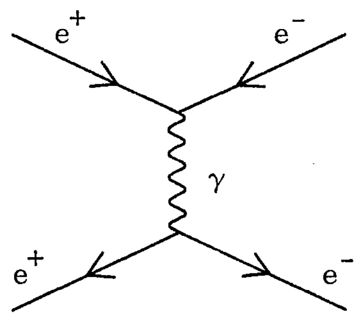
Fig. 3--Total cross section for the production of heavy leptons of mass M, at an electron-positron colliding beam facility, through the reaction $e^+ + e^- \rightarrow \mu'^+ + \mu'^-$. For comparison the uppermost solid line indicates the estimated total cross section for the production of hadrons in the reaction $e^+ + e^- \rightarrow$ hadrons; based on Ref. 36, assuming that no heavy leptons with hadronic decay modes are produced, and assuming this cross section is inversely proportional to the square of the total energy. Also shown for comparison is the dashed curve which indicates the total cross section for the production of hadrons if a heavy sequential lepton of mass 2.0 GeV/c^2 exists.

by varying E by a few hundred MeV around M_ℓ the decay mode particle configurations which signal the existence of the ℓ can be made to appear or disappear.

I should also remind you that for the excited electron, e*, the limit on the heavy lepton mass is <u>not</u> $M_{e*} < E$, but is

$$M_{e*} < 2E, \quad \text{for } e^- + e^+ \to e^{*\pm} + e^\mp \quad . \tag{29}$$

This comes about because the coupling in Eq. (4) allows the diagram



In this case the production cross section of Eq. (26) will be reduced by roughly λ^2, and λ is of course unknown. A similar result holds for the μ^*.

2. Past Searches

The only past search is that carried out by V. Alles-Borelli <u>et al.</u>[37] at ADONE. These experimenters looked for $e^\pm\mu^\mp$ pairs coming from the sequence

$$\begin{aligned} & e^- + e^+ \to \mu'^- + \mu'^+ \\ & \mu'^- \to \nu_{\mu'} + \mu^- + \bar{\nu}_\mu \\ & \mu'^+ \to \bar{\nu}_{\mu'} + e^+ + \nu_e \quad , \end{aligned} \tag{30}$$

or the alternative set of leptonic decay modes. No heavy leptons were found in the mass range of .2 to .8 GeV. <u>But</u> the sensitivity of the search was insufficient[17-19] for conventional heavy sequential leptons throughout this mass range. Heavy sequential leptons produced according to the cross section of Eq. (26) would have been produced at too low a rate to allow detection. In addition the conventional heavy excited leptons, e* or μ^*, could not be detected because these cannot yield the $e^{\pm}\mu^{\mp}$ combination in the final state.

3. Future Searches

Heavy leptons searches will certainly be carried out at all the electron-positron colliding beam facilities now in operation or under construction, Ref. 38 and Table I. I will describe the search we have designed to be

TABLE I

Electron-Positron and Electron-Electron Colliding Beam Rings
(Taken from Ref. 38.)

In operation or discontinued (measured values)	Max Energy (GeV)	Max Luminosity (cm^{-2} s^{-1})
e^-e^- Stanford-Princeton	0.55	5×10^{28}
e^+e^- VEPP-2	0.70	$(1-2) \times 10^{28}$
e^+e^- ACO	0.5	6×10^{28}
e^+e^- ADONE	1.5	3×10^{29}
In pre-operation stage or construction (design values)	**Max Energy (GeV)**	**Max Luminosity (cm^{-2} s^{-1}**
e^+e^- CEA-Bypass	3 (3.5)	10^{31}
e^+e^- VEPP-3	3.5	10^{31}
e^+e^- DORIS (also e^-e^-)	3 (4.5)	10^{33}
e^+e^- SPEAR	3 (4.5)	10^{32}
e^+e^- ACO-II	1.8	10^{32}

carried out at SPEAR, the Stanford Linear Accelerator Center facility.[39] This search method is, I believe, typical of the search methods which will be used at the other colliding beam facilities.

SPEAR, which at the time of writing this paper (May, 1972) is in its early period of operation, will have an initial maximum energy in each beam of $E = 2.5$ GeV and a luminosity of $.5 \times 10^{32}$ (events/cm^2, sec) per interaction region. The maximum energy will be increased later to 4 or 4.5 GeV in each beam.

The search method[40,41] involves the use of a large set of magnetostrictive wire chambers in a solenoidal magnetic field of about 4 kG. Scintillation counters, shower counters, and thick iron plates between wire chambers are used to electronically separate electrons and muons from each other and from hadrons.

The first part of the search method for heavy sequential leptons involves looking for $e^{\pm}\mu^{\mp}$ pairs or for noncolinear $\mu^+\mu^-$ or e^+e^- pairs, coming from the sequence in Eq. (30). Since as discussed in Section III, these leptonic modes compete with hadronic decay modes, the production cross section leading to these modes is reduced below that given in Eq. (26). Further reduction occurs because of experimental factors such as less than 4π steradian angular acceptance. As a typical example, for $M_{\mu'} = 1.5$ GeV the usable cross section for detectable $e^{\pm}\mu^{\mp}$, e^+e^-, $\mu^+\mu^-$ pairs from $\mu'^+ + \mu'^-$ decays is

$$\sigma_{\text{usable}} \approx 4 \times 10^{-2}\, \sigma(e^-e^+ \to \mu^+\mu^-) \approx \frac{8 \times 10^{-34}}{E^2}\ \text{cm}^2 \quad . \tag{31}$$

To produce, say, 4 detectable events per hour, a lower limit for a definitive search, a luminosity of

$$L_{minimum} \approx \left(\frac{E^2}{7}\right) 10^{31} \frac{\text{events}}{\text{cm}^2 \text{ sec}} \tag{32}$$

is required for a beam energy of E GeV. Thus when SPEAR reaches a luminosity of about 10^{31} events/cm^2 sec, the search will begin. If some evidence is found for a heavy sequential lepton, μ', then the total hadronic cross section will be measured in the neighborhood of $M_{\mu'}$. A step in the hadronic cross section, such as that shown in Fig. 3, will be further proof of the existence of the μ'.

I have only discussed above the heavy sequential lepton. Obviously, the noncolinear e^+e^- or $\mu^+\mu^-$ pairs will also be used to search for heavy excited leptons, the e* or the μ*. For example, the noncolinear e^+e^- pair can come from

$$\begin{aligned} &e^+ + e^- \to e^{*+} + e^{*-} \\ &e^{*+} \to e^+ + \gamma \\ &e^{*-} \to e^- + \gamma \quad , \end{aligned} \tag{33}$$

or

$$\begin{aligned} &e^+ + e^- \to e^{*\pm} + e^{\mp} \\ &e^{*\pm} \to e^{\pm} + \gamma \end{aligned} \tag{34}$$

Much more care must be exercised in this search for two reasons.

(a) There are no other decay modes to confirm the existence of the e* or μ*.

(b) There are backgrounds which can simulate the desired signal. For example, noncolinear e^+e^- pairs can be produced by the radiative process

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma \quad , \tag{35}$$

or by the rather copious process[42-44]

$$e^+ + e^- \rightarrow e^+ + e^- + e^+e^- \quad . \tag{36}$$

The major limitations on the electron-proton colliding beam search method is that, except for the special case of Eq. (29), $M_\ell < E$; and E is less than 4 or 4.5 GeV for facilities now being built. In contrast, as discussed in the next section, a 200 GeV photon beam at the 300 GeV CERN accelerator or NAL may produce pairs of heavy leptons with M_ℓ as large as 10 GeV. But, as is also discussed in the next section, photoproduction of pairs is not nearly as clean a search method as is the production by e^-e^+ colliding beams. For this reason, and for many other reasons, much higher energy electron-positron colliding beam facilities are now being discussed. For example, physicists at the Lawrence Berkeley Laboratory, at SLAC and elsewhere are considering the design[36] of a 15 GeV electron-positron colliding beam facility. This facility, called PEP in the design stage,[45] would have 15 GeV in each beam so that the limit on M_ℓ would be raised to 15 GeV.

B. Photoproduction of Heavy Leptons

1. The Method

For heavy leptons which are Dirac point particles with unit charge, the production cross section for the photoproduction of pairs of these particles can be calculated quite well.[46,47] For photoproduction on a nucleus (Nuc) we have the following processes

$$\gamma + \text{Nuc} \rightarrow e^+ + e^- + \text{Nuc} \quad \text{(coherent production on the entire nucleus)} \tag{37a}$$

γ + p or n in nucleus $\rightarrow e^+ + e^-$ + free p or n (quasi-elastic production on protons or neutrons in nucleus) (37b)

γ + p or n in nucleus $\rightarrow e^+e^-$ + free nucleon + additional hadrons (inelastic production on protons or neutrons in nucleus) (37c)

One of the most recent complete calculation on these processes is that of Kim and Tsai.[46] They give the results of a typical calculation for a beryllium target for $.1 \leq M_\ell \leq 6$ GeV and k, the photon energy, up to 200 GeV. This calculation shows that the process in Eq. (37c) can usually be ignored compared to the processes in Eqs. (37a) and (37b). Figure 4 is a plot of the total production cross section.

The differential cross section[46] for the production of one lepton at an angle θ and momentum p, summed over all allowed momenta and angles of the other lepton and all hadronic final status, is

$$\frac{d\sigma}{d\Omega dp} = \frac{2\alpha^3}{\pi K}\left(\frac{E^2}{M_\ell^4}\right)\left[\frac{2x^2-2x+1}{(1+r)^2} + \frac{4x(1-x)r}{(1+r)^4}\right]\chi \tag{38}$$

Here k is the photon energy, M_ℓ is the lepton mass, E is lepton's total energy, $x = E/k$, $\gamma = E/M_\ell$, and

$$r = \gamma^2\theta^2 = E^2\theta^2/M_\ell^2 \tag{39}$$

χ, defined exactly in Ref. 46, is a function of the minimum four-momentum transfer to the hadronic vertex and the form factors at that vertex. From Eq. (38) we observe the following well-known property of the photoproduction of pairs. When θ is small so that $r \ll 1$,

$$\frac{d\sigma}{d\Omega dp} \sim \frac{1}{M_\ell^4} \quad . \tag{40}$$

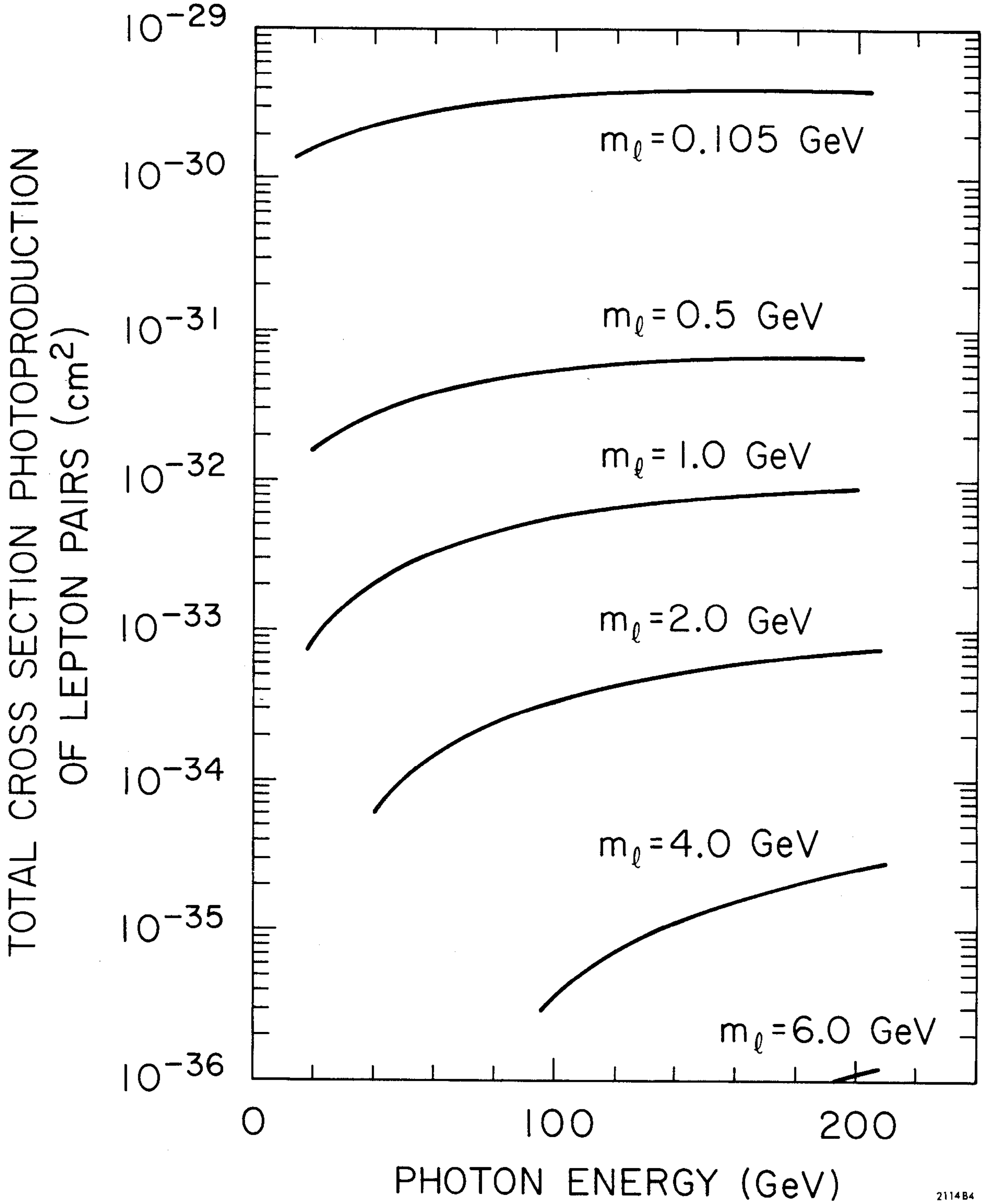


FIG. 4--Total cross section for the photoproduction on beryllium of pairs of heavy leptons of mass m_ℓ. Taken from Ref. 46.

Thus at small angles the production of high mass heavy leptons is much suppressed compared to electron or muon production. On the other hand, when $\theta E \gtrsim M_\ell$, then $r \gtrsim 1$ and $d\sigma/(d\Omega dp)$ is, except for the χ term, independent of M_ℓ. Hence the crude rule that at large angles, all leptons will be produced in roughly equal numbers.

Separated photon beams need not be used to produce lepton pairs. For example, at electron accelerators, electrons hitting a target of 5 or 10 radiation lengths lead to a double process in the same target,[12, 48, 49] namely

$$\begin{aligned} &e^- + \text{Nucleus} \rightarrow e^- + \text{Nucleus} + \gamma \\ &\gamma + \text{Nucleus} \rightarrow \ell^+ + \ell^- + \text{hadrons} \quad . \end{aligned} \tag{41}$$

At proton accelerators the following sequence of processes can occur in a thick target[50]

$$\begin{aligned} &p + \text{Nucleus} \rightarrow \pi^o + \text{hadrons} \ , \\ &\pi^o \rightarrow \gamma + \gamma \quad , \\ &\gamma + \text{Nucleus} \rightarrow \ell^+ + \ell^- + \text{hadrons} \ . \end{aligned} \tag{42}$$

But the processes of Eq. (42) cannot always be distinguished from other hypothetical processes for making lepton pairs in proton-proton or proton-nucleus collisions. Therefore we postpone further discussions of all proton-proton or proton-nucleus searches to the next section.

Since the relatively high mass heavy leptons under discussion here have very short lifetimes, they must, of course, be detected through their decay modes. Their detection through their hadronic decay modes, if they are heavy sequential leptons, is very difficult because of the copious direct production of hadrons in photoproduction. The total cross section for the production of hadrons by photons at high energy is about 10^{-28} cm^2, which is 10^4 to 10^8 times larger than the heavy lepton production cross section in Fig. 5. Therefore part and future searches for heavy sequential leptons almost always rely on the detection of the electrons, the muons, or the neutrinos produced in the leptonic decay modes. For the heavy excited lepton the electron, muon or γ must be detected. We now turn to these searches.

2. Past Searches

I only know of one search for short-lived heavy leptons carried out at an electron accelerator. This is a recent search[48,49,51] carried out at SLAC in which an 18 GeV, high intensity electron beam was used in the production process of Eq. (41). All charged particles were stopped very quickly by a thick wall of matter. However a heavy lepton with a lifetime shorter than 10^{-10} seconds would decay before stopping. The decay mode

$$\mu'^- \rightarrow \nu_{\mu'} + \pi^- \tag{43}$$

would yield high energy, $\nu_{\mu'}$ neutrinos which would penetrate the wall.[51,52] Some of these $\nu_{\mu'}$ neutrinos might then interact in optical spark chambers, placed downstream of the wall; and these interactions would lead to hadron productions through the production and immediate decay of the μ'. No events which require this explanation were found, and in general no other clear evidence was found for the production of the μ'. <u>But</u> the experiment did not have sufficient sensitivity.[48,49] And the production, by the processes of Eq. (41), of heavy sequential leptons with $M_{\mu'} > .5$ GeV was <u>not</u> excluded.

This is perhaps a good place to comment on why there have been no searches for short-lived heavy leptons photoproduced directly in bubble chambers or

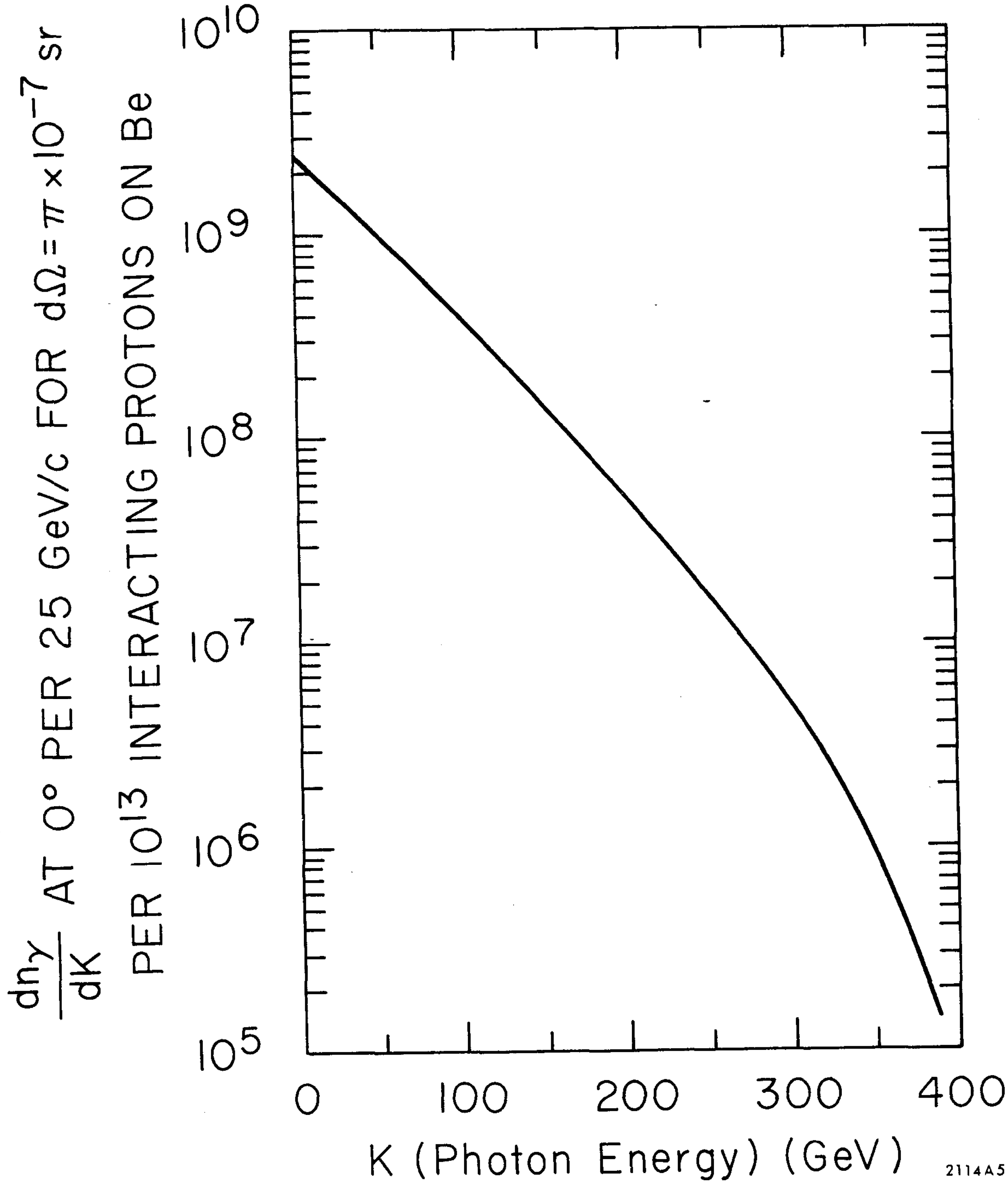


FIG. 5--Example of a photon beam which can be produced at a high energy proton accelerator. Taken from Ref. 53.

streamer chambers. After all, particles with lifetimes as short as 10^{-10} seconds, the hyperons for example, are seen directly in track chambers. The problem is demonstrated by Eq. (40). The photoproduction of electrons and positrons at small angles overwhelms all other pair production of leptons at small, or large, angles. A possible solution has been proposed by Heusch and Sandweiss.[50]

3. Future Searches

High energy photon beams have been produced at Serpukov and will be produced at NAL and at the 300 GeV CERN accelerator. I shall, however, restrict my discussion to the searches planned at NAL in accordance with the apology I made in Section I. A general summary of proposed NAL heavy lepton searches by photoproduction, and by other methods, has been given by Heusch and Sandweiss.[50] Two proposals[53,54] which can include heavy lepton searches have been accepted by NAL.

Lee *et al.*[52] plan to use a photon beam with a maximum energy of 400 GeV. The beam hits a 0.1 radiation length beryllium target. Spark chamber hodoscopes, an analyzing magnet, and scintillation and shower counters are used to select and identify e's, μ's and π's of greater than 30 GeV/c momentum produced at between 20 to 50 mrad to the photon beam direction. The trick is to search for those events in which both heavy leptons have decayed in the decay modes

$$\begin{aligned} \mu' &\rightarrow \nu_{\mu'} + \mu + \nu_\mu \\ \mu' &\rightarrow \nu_{\mu'} + e + \nu_e \\ \mu' &\rightarrow \nu_{\mu'} + \pi \quad , \end{aligned} \tag{44}$$

these being the decay modes in which just one charged particle is produced. Furthermore they demand that both charged particles appear on the same side of the beam. Finally the transverse-momentum spectrum of e, μ, or π, for these decay modes, has a sharp upper cutoff at $p \approx M_{\mu'}/2$.

To give the reader a rough feeling for the sensitivity of such experiments I have shown in Fig. 5, the expected photon spectrum for a photon beam of maximum energy 400 GeV, produced at a proton accelerator. For a crude calculation of the total rate of production of a heavy lepton of 4.0 GeV/c^2 mass I take an average production cross section of 3×10^{-35} cm^2 from Fig. 4; and I assume that the accelerator will on the average provide 10^{12} protons per pulse and 1000 pulses per hour to the individual experiment. Then in a heavy lepton production target consisting of 1.0 radiation length of beryllium, one would obtain

$$\frac{\text{total number of mass 4.0 GeV/c}^2\text{ leptons}}{\text{hour}} \sim 10$$

Experiments using small solid angle detectors, such as the ones being described in this section, would appear to have a fractional acceptance for each decay particle from the heavy lepton of about 10^{-1} to 10^{-3}. This includes the angular and momentum acceptance; and the fractional decay into the desired decay mode. Therefore

$$\frac{\text{detected number of mass 4.0 GeV/c}^2\text{ leptons}}{\text{hour}} \sim 10^{-1} \text{ to } 10^{-5}$$

Thus the sensitivity of this method, under the conditions given here may not be sufficient, in view of the necessity of distinguishing the heavy lepton signal from possibly large background. Therefore the experiments which are proposed[53] tend to emphasize maximum intensity primary proton beams, namely 10^{13} protons per second; and long running times, namely 1000 hours. Finally, sufficiently large solid angle detectors, would permit the search for heavy sequential mesons to be extended into the 7 to 10 GeV/c^2 mass range.

The proposed experiment of Cronin and Piroué[54] differs from the experiment just described in that the secondary particles will be studied at larger angles — 80 mrad in the laboratory which is about 90° in the p-p center-of-mass system. This has the advantage that background will be reduced, but so will the sensitivity for the secondary particles from the decays of the heavy leptons. In this experiment it is initially planned to study only one particle at a time. Muons or electrons with high transverse-momentum will be taken as indicative of the existence of heavy leptons or of the existence of the weak intermediate boson W or of the existence of a heavy photon.

C. Productions of Heavy Leptons in Proton-Proton and Proton Nucleus Collisions

1. The Method

This search method is perhaps the most uncertain[50] with respect to its efficiency and sensitivity. The problem is that we know very little about the production process. We do know however the muon pair spectrum, $d\sigma/dM_{\mu\mu}$, produced in the pioneer experiment of Christensen et al.[55] in which the reaction

$$p + \text{Nucleus} \rightarrow \mu^{+} + \mu^{-} + \text{hadrons} \tag{44}$$

was studied. (Here $M_{\mu\mu}$ is the invariant mass of the muon pair defined by $M_{\mu\mu}^{2} = [p^{+} + p^{-}]^{2}$, where $p^{\pm}$ is the four-momentum of the $\mu^{\pm}$.) We know that speculative theories[56-59] can be used to fit that data and to make predictions at higher energies for the production of electron pairs, muon pairs or heavy lepton pairs. And it is upon these speculative predictions that the search method must be based.

Suppose that the differential cross section $d\sigma/dM_{\mu\mu}$ of Eq. (44) is measured up to $M_{\mu\mu,\max}$. Then if one assumes that the lepton pair production is equivalent to pair production by a virtual photon, one can calculate directly the cross section for the production of a pair of charged heavy leptons, provided the heavy lepton mass M_ℓ is

$$2M_\ell < M_{\mu\mu,\max} \tag{45}$$

Thus Gerstein et al. give the relationship[11]

$$\sigma(p+p \to \ell^+ + \ell^- + \text{hadrons}) = \int_{2M_\ell}^{M_{\mu\mu,\max}} \left(\frac{d\sigma}{dM_{\mu\mu}}\right) \left(1 - \frac{4M_\ell^2}{M_{\mu\mu}}\right)^{\frac{1}{2}} \times \left(1 + \frac{2M_\ell^2}{M_{\mu\mu}}\right) dM_{\mu\mu} \tag{46}$$

If

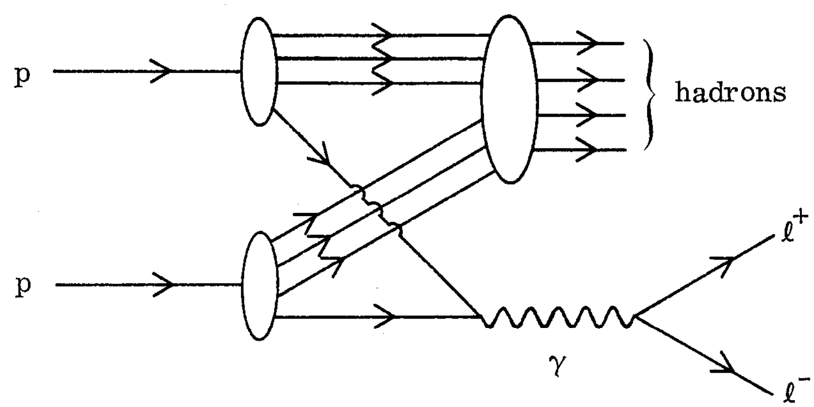
$$2M_\ell \ll M_{\mu\mu,\max} , \tag{47}$$

we have the approximation

$$(p+p \to \ell^+ + \ell^- + \text{hadrons}) \sim \int_{2M_\ell}^{M_{\mu\mu,\max}} \left(\frac{d\sigma}{dM_{\mu\mu}}\right) dM_{\mu\mu} \quad ; \tag{48}$$

which is equivalent to the assumption that at large angles the virtual photoproduction of leptons is roughly independent of their mass.

To extend these considerations to higher energy, it is necessary to use even more speculative ideas. For an example of such predictions I refer the reader to those made by Berman et al.[60] They used the Drell and Yan model,[56] in which the parton model diagram



is used to calculate the reaction

$$p + p \rightarrow \ell^+ + \ell^- + \text{hadrons} \tag{50}$$

(The intermediate straight solid lines in the diagram are all partons.) Here a parton-antiparton pair annihilates to form the heavy lepton pair. Very roughly the total cross section for the reaction of Eq. (50) is

$$\sigma(pp \rightarrow \ell^+\ell^- \text{hadrons}) \sim \frac{\alpha^2}{M_\ell^2} F \tag{51}$$

if the total energy is sufficiently above the $\ell^+\ell^-$ production threshold of about $2M_\ell$. The term (α^2/M_ℓ^2) is just the cross section for parton + antiparton $\rightarrow \ell^+\ell^-$. F is a number less than 1 and probably very small — of the order of 10^{-2} to 10^{-4}. F is a measure of the probability of finding a parton in one proton and an antiparton in the other proton with the momentum relationships required to make the $\ell^+\ell^-$ pair. It is F being much less than 1 which gives the process in Eq. (50), a small cross section compared to the process $e^- + e^+ \rightarrow \ell^- + \ell^+$ discussed in Section V.A.

Of course once measurements are made of the direct production cross section for electron or muon pairs with large invariant mass, then the situation will be clearer. Until that time, it seems best to restrict the possible use of proton-proton or proton-nucleus collisions for heavy lepton searches to the higher mass range which the methods previously discussed cannot reach. This is approximately $M_\ell \geq 10$ GeV. From Eq. (51) for $M_\ell = 10$ GeV

$$\sigma(pp \rightarrow \ell^+\ell^- \text{ hadrons}) \sim 10^{-34} \text{ F cm}^2 \ . \tag{52}$$

Thus in spite of our lack of knowledge of the production cross section, processes like that in Eq. (50) are of great interest to the experimenter searching for heavy leptons because they offer the possibility of going to very large lepton masses. This is particularly true for proton-proton colliding beam experiments if the luminosity is sufficiently high. As an example of this luminosity requirement we note that the luminosity requirement we note that the luminosity of the ISR is expected[61] to reach about 10^{30} events/cm^2 sec. But from Eq. (52), this would yield only about .4 F pairs per hour of mass 10 GeV heavy leptons — a rate too small for a heavy lepton search. But a luminosity of 10^{32} or 10^{33} cm^{-2} sec^{-1} would allow a very profitable heavy lepton search to be made at future proton-proton colliding beam facilities.

Returning to conventional proton accelerators we suppose that the primary proton beam has an average intensity of 10^{13} protons per second. Then in a one meter hydrogen target (or its equivalent), the primary proton beam can produce 1.5×10^7 F pairs per hour of 10 GeV mass heavy leptons! Thus there can be copious production of heavy leptons using the primary proton beam.

2. Past Searches

No searches of sufficient sensitivity for short-lived heavy leptons produced by p-p or p-nucleus collisions appear to have been carried out.

3. Future Searches

Because of the luminosity considerations discussed above, searches in the near future appear to be most fruitful at conventional proton accelerators. However, given the tremendous uncertainties in the theoretical predictions, searches at proton-proton colliding beam facilities should not be neglected.

Both sorts of searches appear to be contemplated although I know of no published descriptions of such searches. The search method appears to be similar to that planned for heavy lepton pairs which are photoproduced, as described in the last section. Electrons, muons and pions of high transverse momentum may be used in the search with $\mu^{\pm}$ $e^{\mp}$ pairs providing the clearest signal.

D. Searches for Heavy Excited Leptons Using Lepton-Proton Scattering

1. The Method

If the vertex of Eq. (4) is assumed then the reactions

$$e + p \to e^* + p \,, \qquad e^* \to e + \gamma \tag{53a}$$

or

$$\mu + p \to \mu^* + p \,, \qquad \mu^* \to \mu + p \tag{53b}$$

can occur.[62] The cross section depends of course on λ^2. The reaction can be identified by looking for a sharp peak other than the elastic peak in the momentum spectrum of the recoil proton. Therefore this search method does not require any knowledge of the nature of the e* or μ^*, it only requires the assumption of an electromagnetic coupling of the e or μ to the heavy lepton.

2. Past Searches

Experimenters at Orsay,[63] DESY,[64] and CEA[65,66] have used this method to search for e* heavy excited leptons. But <u>none</u> have been found. Figure 6 summarizes the limits on λ set by these searches.

3. Future Searches

Melissinos *et al.*[67] are now completing a muon-proton scattering experiment at BNL which includes a search for the μ^*. I do not know of any other searches of this sort which are being planned for the near future. But I should note that this search method is not at all exhausted. Muon or electron beams of up to 20 GeV are available at SLAC or BNL. Higher energy lepton beams will be soon available at the new higher energy accelerators. For a primary lepton beam of energy E this search method extends to excited lepton masses $M_{\ell *} \approx \sqrt{2EM_p}$. However, one should remember that the square of the minimum

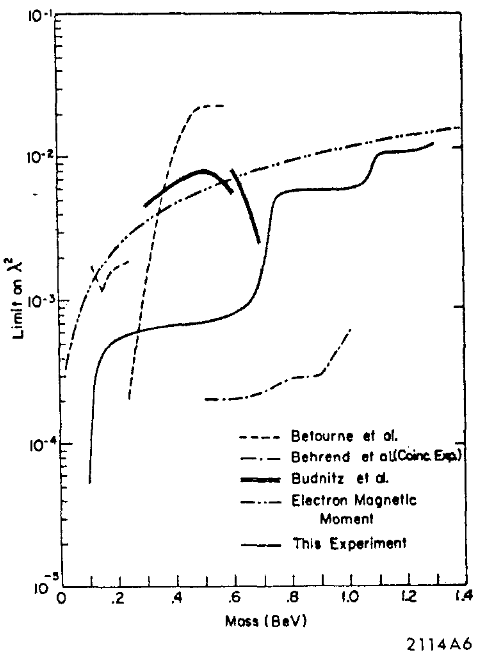


FIG. 6--Comparison of upper limits on the values of λ^2 from various experiments (see Refs. 63-65). The limits on λ^2 imposed by the anomalous magnetic moment of the electron are also shown. It should be noted that considerably different procedures were used for calculating the quoted limits in the experiments shown above. The limits on λ^2 ascribed to Budnitz et al. (see Ref. 65), were calculated from the limits quoted on their cross section measurements. "This Experiment" refers to Ref. 66. Figure and caption (with slight alteration) taken from Ref. 66.

four-momentum-transfer $|q^2|_{min}$ goes as

$$|q^2|_{min} = \frac{M_{\ell*}^4}{4E^2} \quad . \tag{54}$$

The form factors at the proton vertex will lead to a rapid loss of sensitivity as $|q^2|_{min}$ increases.

E. Searches for Heavy Excited Leptons in Lepton Bremsstrahlung

1. The Method

This search method, which is closely related to the method discussed in the last section, consists simply of the study of the invariant mass $M_{e\gamma}$ in the bremsstrahlung process

$$e + \text{nucleus} \rightarrow e + \gamma + \text{nucleus} \quad . \tag{55}$$

An exactly similar method can be used to search for the μ^* in muon bremsstrahlung.

2. Past Searches

No evidence for the e* has been found in studies of electron bremsstrahlung.[23,68,69] The most extensive study covers the mass range of .1 to 1.2 GeV/c^2. But as pointed out by Lichtenstein,[23] these bremsstrahlung experiments are quite a bit less sensitive for heavy lepton searches compared to the lepton-proton scattering experiments previously described.

I have already noted in Section III.A that Ramm has pointed out a possible μ^* effect in the only muon-proton bremsstrahlung experiment yet performed.

3. Future Searches

A very high energy search for the e* in electron bremsstrahlung has been proposed by J. F. Crawford et al.[70] This experiment, to be carried out at NAL, is designed for electron beams of several hundred GeV energy.

F. Searches for Heavy Lepton Using Lepton-Proton Inelastic Scattering

Lepton-proton inelastic scattering can be used to search for heavy leptons. However we postpone the discussion of this search method to Section VI. C where we discuss lepton-proton inelastic scattering in detail.

G. Miscellaneous

It is of interest to those interested in heavy leptons, that a test[10] has recently been performed of the special pair hypothesis of Eq. (6). The reaction

$$\mu^- + C_\mu \rightarrow e^+ + C_0$$

was used; and one possible event was found. Using a calculation of Kisslinger[9] the ratio of the hypothetical coupling constant of the $\mu^- e^+$ to hadrons was found to be $\lesssim 0.1$ of G_V, the conventional weak interaction vector coupling constant.

VI. SEARCHES FOR ANOMALOUS INTERACTIONS OF LEPTONS

By the term anomalous interaction I mean an interaction of a lepton which is not explained by conventional quantum electrodynamics or conventional, first order, weak interaction theory. We search for such anomalies in the hope of finding some new clues for understanding the relation of the muon to the electron; and in the hope of gaining some insight into the fundamental nature of these leptons which are, as far as we can tell, perfect Dirac point particles.

This section is a potpourri of the various possible anomalous effects which have interested me in the past few years. Thus it is not intended to be a complete treatment. And I shall not treat again those effects which have been described in my heavy lepton discussions — effects like the Ramm $\mu^* \rightarrow \mu + \pi$ resonance.

A. Anomalies in Quantum Electrodynamic Properties of the Leptons

As has been discussed in several summary papers,[71, 72] one of the most recent being that of Brodsky and Drell;[72] there are no outstanding anomalies or discrepancies. This conclusion includes some very recent measurements of the colliding beam processes $e^+ + e^- \rightarrow e^+ + e^-$ and $e^+ + e^- \rightarrow \mu^+ + \mu^-$.

B. The X-ray Spectra of Muonic Atoms

Recently the measurements of the X-ray spectra of muonic atoms have increased in precision.[73, 74] This increased precision seemed to lead to a number of discrepancies[73] between the measurements and the theoretical calculations of the spectra. However, Sundaresan and Watson[75] have recalculated the vacuum polarization terms in the theory; and this recalculation has removed almost all discrepancies.[75] Therefore at present there is no clear evidence for anomalous muon interactions in muonic atoms.

C. Comparison of Electron-Proton and Muon-Proton Elastic Scattering

A very general way to search for anomalous behavior of the electron or the muon[76-81] is to compare electron-proton and muon-proton elastic scattering. For a fixed energy of the incident lepton in the laboratory system, the differential cross section, $(d\sigma/dq^2)_{\ell p,\, elas}$ is a function only of q^2, the square of the four-momentum transferred from the lepton vertex. Explicitly

$$q^2 = (E-E')^2 - (\underset{\sim}{p} - \underset{\sim}{p}')^2 \tag{56}$$

where $E, \underset{\sim}{p}$ and $E', \underset{\sim}{p}'$ are the energy and momentum of the incident and final lepton respectively.

To make the comparison we define the ratio

$$\rho_{elastic}(q^2) = \left[(d\sigma/q^2)_{\mu p,\, elas} / (d\sigma/dq^2)_{ep,\, elas}\right] \text{corrected for mass} \tag{57}$$

The notation "corrected for mass" means that the ratio has been adjusted for the mass difference between the electron and the muon; this mass difference results in slight differences in the Rosenbluth formula.[79,80] The differential cross sections used in Eq. (57) have also been corrected for radiative effects.

If there is no anomalous behavior exhibited by the electron or the muon in elastic scattering then we expect

$$\rho_{\text{elastic}}(q^2) = 1.0 \quad . \tag{58}$$

(Of course, we would also obtain this result if both leptons exhibited exactly the same anomalous behavior.)

Two comparisons of electron-proton and muon-proton elastic scattering have been performed.[80,81] ρ_{elastic} for the second and better experiment[81] is shown in Fig. 7. We see that ρ_{elastic} on the average is less than 1.0, its average value is

$$\overline{\rho_{\text{elastic}}} = .92 \pm .01 \tag{59}$$

The earlier experiment showed a similar deviation with

$$\overline{\rho_{\text{elastic}}} = .88 \pm .04 \tag{60}$$

Unfortunately, such differences can appear, if either the muon-proton or the electron-proton data was incorrectly normalized. The authors of these comparisons have no evidence that such normalization errors have been made,[80,81] but it is very difficult to exclude overall normalizations errors of about 5% on each experiment. Therefore the conventional assumption is that the deviations which appear in Eqs. (59) and (60) are caused by normalization errors. However, later in this section, we shall speculate on the significance of these deviations assuming that they are not caused by normalization errors.

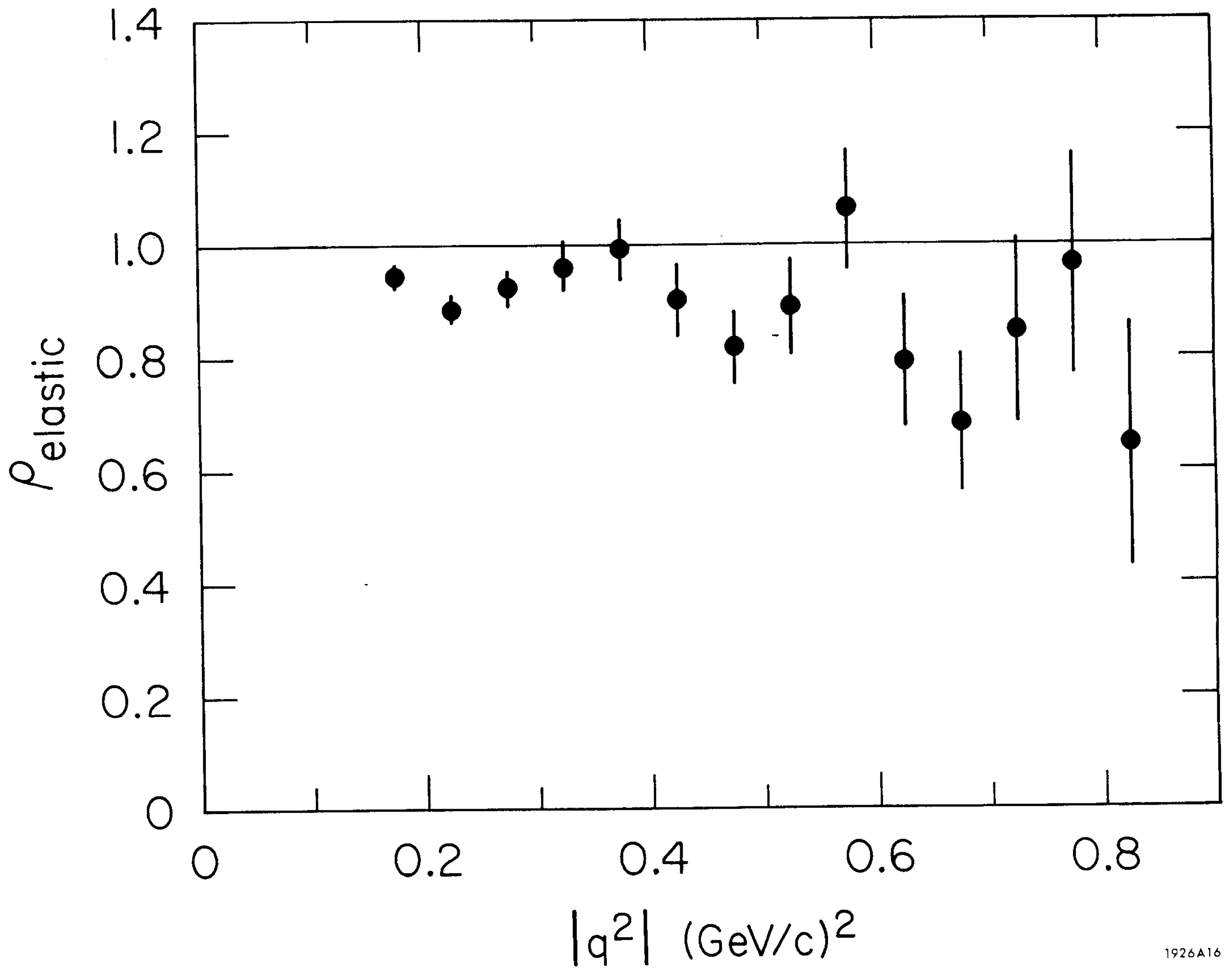
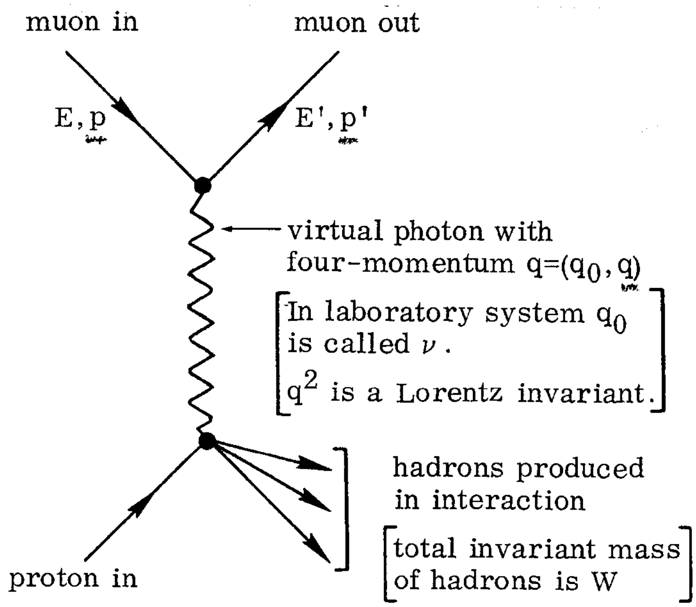


FIG. 7--$\rho_{elastic}(q^2)$ is the ratio of the muon-proton elastic differential cross section to the electron-proton elastic differential cross section, corrected for the difference in the lepton masses. The principle of muon-electron universality requires $\rho_{elastic} = 1$ for all values of q^2. The error bars represent only statistical errors; the systematic uncertainties are discussed in the text. The data is taken from Ref. 81.

D. Comparison of Electron-Proton and Muon-Proton Inelastic Scattering

Another very general way to search for anomalous behavior of the electron or the muon is to compare electron-proton and muon-proton inelastic scattering, as has been done recently using electron data[82] and muon data from SLAC.[76-78] The kinematics of lepton-proton inelastic scattering are a bit complicated so that I shall digress for a moment to discuss the experimental method and kinematics. The relevant kinematics, for the muon case, are shown below for one-photon-exchange.



KINEMATICS
(in laboratory system)

$\nu = q_0 = E - E'$

$\mathbf{q} = \mathbf{p} - \mathbf{p}'$

$q^2 = q_0^2 - (\mathbf{q})^2$

$|q^2| < 2M\nu$

M is proton mass

$W^2 = 2M\nu + M^2 - |q^2|$

In the experiments used in the comparison only the inelastically scattered charged lepton is detected. No attempt is made to detect any of the hadrons produced. This inelastic scattering experiment then sums experimentally over the different hadronic states which can be produced. As may be deduced from the foregoing diagram the reaction is then completely described by three independent kinematic quantities. These we take to be E (the initial lepton's energy), q^2 (the square of the four-momentum transferred from the lepton vertex) and ν (the laboratory energy of the virtual photon given by E-E'). The experiment consists of the measurement of the double differential cross section of the inelastically scattered muon. This differential cross section, $d^2\sigma/dq^2\, d\nu$, is a function of E, ν and q^2. It is convenient for experimental reasons to define a slightly different variable

$$K = \nu - |q^2|/2M \quad . \tag{61}$$

K is the equivalent energy that a real photon must have to give the same total energy in the photon-proton center-of-mass system.[83] Also,

$$d^2\sigma/dq^2\, d\nu = d^2\sigma/dq^2\, dK \quad , \tag{62}$$

and I shall use the latter from now on.

We define the ratio

$$\rho_{inelastic}(q^2, K) = \left[(d^2\sigma/dq^2 dK)_{\mu p}/(d^2\sigma/dq^2 dK)_{ep}\right]_{\text{corrected for mass}} \tag{63}$$

which is again corrected for differences in the lepton masses. Figure 8 gives the value of $\rho_{inelastic}(q^2, K)$ for various values of q^2 and K. We see in Fig. 8 that within the errors $\rho_{inelastic}(q^2, K)$ is always about 1.0, but on the average $\rho_{inelastic}(q^2, K)$ seems to be a little less than one. In comparing these two experiments we must also consider the possibility of relative overall normalization errors, as we did in the elastic case. We have done so, and we estimate that the overall relative normalization error due to systematic uncertainties may be as large as 8%. With this consideration we see that none of the individual deviations of $\rho_{inelastic}(q^2, K)$ from unity are significant. But the average value

$$\bar{\rho}_{inelastic} = .92 \pm .02 \tag{64}$$

is less than 1.0. The error in Eq. (64) is purely statistical and does not include the possible maximum overall normalization error of 8%.

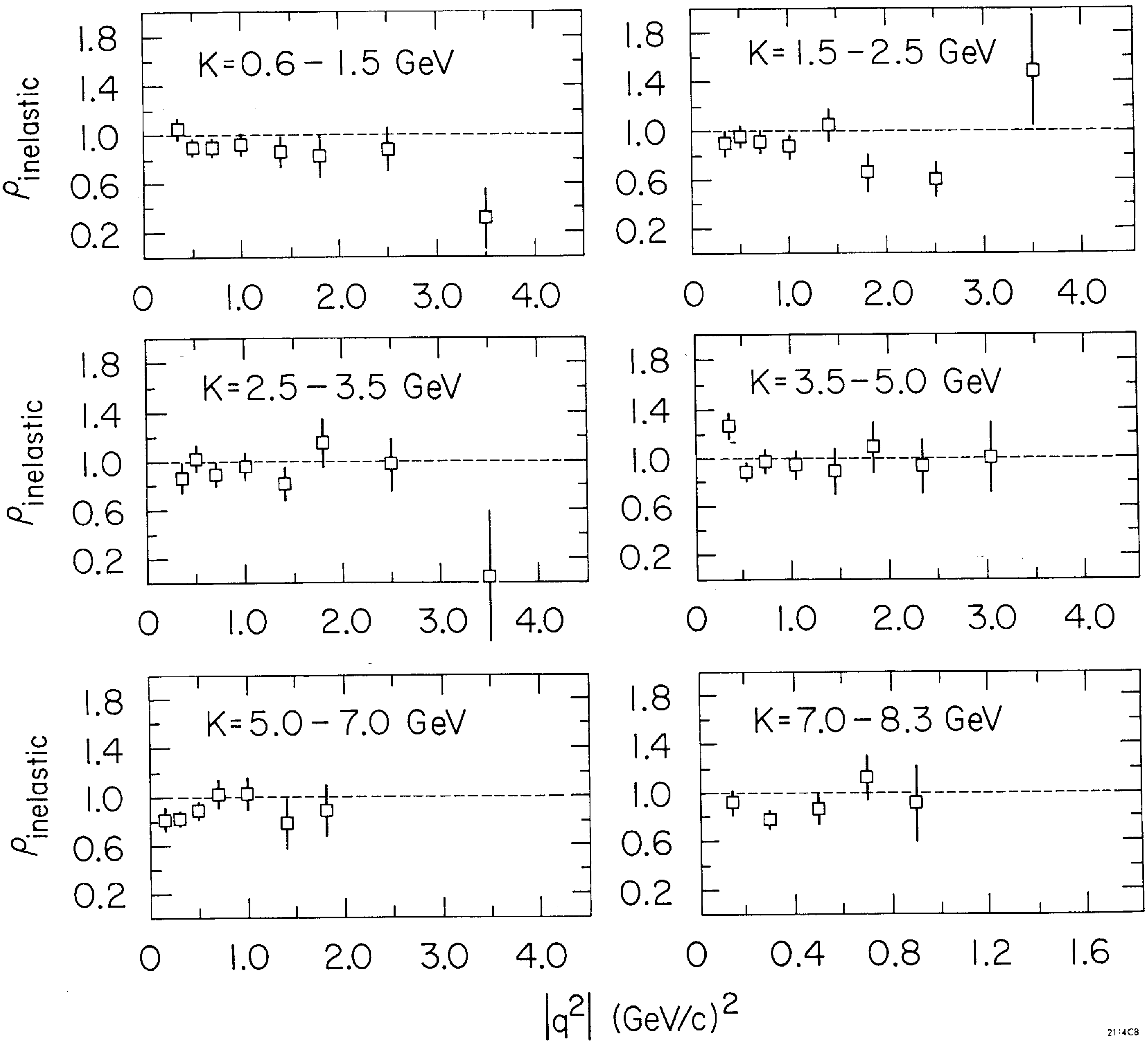


FIG. 8--For each K interval, the figure gives the values of $\rho_{inelastic}(q^2, K)$ versus q^2. $\rho_{inelastic}(q^2, K)$ is the ratio of the muon-proton inelastic scattering cross section to the electron-proton inelastic scattering cross section, corrected for the difference in the lepton masses. q^2 is the square of four-momentum transferred from the lepton. $K = \nu - |q^2|/2M$ where M is the proton mass and ν is the energy lost by the lepton in the laboratory system. K is in GeV. The error bars represent only statistical errors. The systematic uncertainties are discussed in the text. For the principle of muon-electron universality to be valid $\rho_{inelastic}$ should equal unity for all values of q^2 and K.

Because of the normalization uncertainties in the elastic and inelastic comparisons, it is not possible to draw definite conclusions from these comparisons with respect to the possible anomalous behavior of the electron or the muon in these scattering processes. However it is certainly useful to use the results summarized in Eqs. (59), (60), and (64) as a starting point for speculations about possible anomalies. These speculations are the subject of the next three sections.

E. Speculations on the Form Factor of the Muon

One obvious way to make the muon scattering cross sections smaller than the corresponding electron scattering form factors is to ascribe a form factor[85] to the muon while maintaining the point particle nature of the electron. It is conventional[76,86] to use the form factor

$$G_\mu(q^2) = 1/\left[1-q^2/\Lambda_\ell^2\right] . \tag{65}$$

in discussing the properties of the charged leptons. For elastic and inelastic scattering where q^2 is spacelike, hence negative in our metric, Eq. (65) takes the form

$$G_\mu(q^2) = 1/\left[1+|q^2|/\Lambda_\ell^2\right] . \tag{66}$$

But if we look at the muon-proton inelastic and elastic experiments, with no preconceived notions as to how the muon-electron difference might behave with q^2 we would not use the form factors $1/\left[1+|q^2|/\Lambda_\ell^2\right]$. Instead we would use a form which gives a roughly q^2 <u>independent</u> difference between the muon and electron cross sections in the q^2 range covered by the experiments. We would of course also require $G_\ell(0)=1$. A simple example of such a model is one in which the electron is indeed a point Dirac particle so that $G_e(q^2)=1$, and

$$G_\mu(q^2) = (1-b) + b/\left(1 + |q^2|/\Lambda_\mu^2\right)$$

$$= 1 - \left(b|q^2|\right)/\left(|q^2| + \Lambda_\mu^2\right) \qquad 0 \leq b \leq 1 \tag{67}$$

Then in the scattering experiments as $|q^2|$ increases

$$\rho_{\text{inelastic}}(q^2, K) = \rho_{\text{elastic}}(q^2) \xrightarrow[|q^2| \to \infty]{} (1-b)^2 \quad .$$

Thus at high values of $|q^2|$ only a "normalization difference" would be observed. The form factor of Eq. (67) could come from the following model. Take the muon to have (1-b) of its electric charge concentrated in a point and b of its electric charge spread out in a halo of radius $\sqrt{6}/\Lambda_\mu$. To fit the "normalization differences" found in the inelastic and elastic experiments, b would have a value in the vicinity of .05. Thus this model may be described as a mostly point muon with a small fraction of the electric charge in a halo around the point.

Up to now we have been concerned with fitting a form factor to the high energy scattering experiments. But, we must realize that any such form factor modification would affect the value of the muon gyromagnetic moment, g_μ. The very high precision measurement[87] of $(g_\mu-2)$ of the muon agrees with the predictions of quantum electrodynamics to a very high precision, and consequently imposes a strong constraint on the hypothetical muon form factor. The modification to a_μ^{theory} due to the inclusion of the form factor of Eq. (66) at each real muon vertex has been calculated.[88] The modification may be expressed as multiplication of a_μ by the factor

$$1 - (4/3)\left(m_\mu^2/\Lambda_\mu^{g^2}\right) \tag{68}$$

Then with 95% confidence[87]

$$\Lambda_\mu^g > 7.0 \text{ GeV/c} \quad . \tag{69}$$

This result imposes a limit on the parameters b and Λ_μ from Eq. (67). The g-2 experiment is essentially a low $|q^2|$ measurement; if we approximate Eqs. (66) and (67) in this limit we find

$$b/\Lambda_\mu^2 \approx 1/\Lambda_\mu^{g^2} \quad .$$

So, by Eq. (69)

$$b/\Lambda_\mu^2 < .02 \text{ with 95\% confidence} \quad .$$

Unfortunately this limit does not give very good agreement with the high energy scattering results, as we can see by considering the region in which $|q^2|/\Lambda_\mu^2 \ll 1$ where:

$$1 - \rho_{\text{inelastic}} = 1 - \rho_{\text{elastic}} \approx 2b|q^2|/\Lambda_\mu^2 < .04|q^2|$$

with 95% confidence. For $|q^2|$ values less than 1 the "normalization differences" are then limited to less than 4% with 95% confidence, which, while not inconsistent, is on the edge of compatability with the data. Thus the function given in Eq. (67) is not a very good choice for the muon form factor.

What is required is a form factor which is a more rapid function of q^2. An example of such an expression is

$$G_\ell(q^2) = 1 - b + b/\left(1 + (q^2)^2/\Lambda_\ell^4\right) \quad . \tag{70}$$

In the limit $(q^2)^2/\Lambda_\ell^4 >> 1$, this form gives

$$G_\ell(q^2) \to 1 - b_\ell$$

and

$$\rho_{\text{inelastic}} = \rho_{\text{elastic}} \to \frac{(1-b_\mu)^2}{(1-b_e)^2} \quad . \tag{71}$$

Equation (71) would look like a normalization discrepancy. We have fit our inelastic data[78] to this form assuming b_e=0 and find

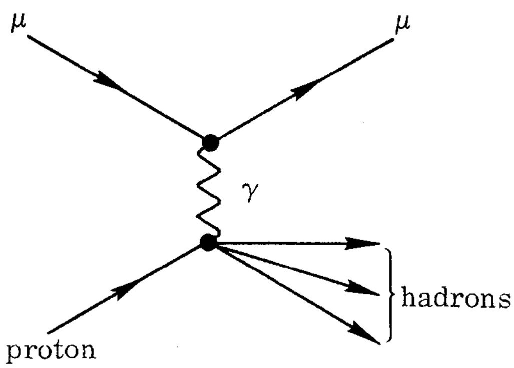
$$b_\mu = .062 \pm .032 \ , \qquad \Lambda_\mu^{-4} = 3.2 \pm 3.9 \ (\mathrm{GeV/c})^{-4} \ .$$

Equation (70) with the parameters given above is consistent with the g_μ experiment[87] which led to the limit on Λ_μ^g given in Eq. (69). It is similarly consistent with $e^+ + e^- \rightarrow \mu^+ + \mu^-$ experiments.[89,90]

E. Speculations on Anomalous Lepton-Hadron Interactions[84]

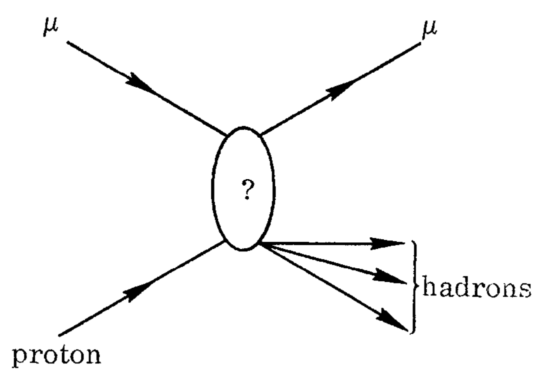
In the previous section we have attempted to explain the various experimental data in terms of a muon form factor. An alternate approach is to postulate a special muon-hadron interaction. Such an interaction can conceivably explain the "normalization differences" in both the elastic and inelastic scattering experiments and yet have only very small effects on the gyromagnetic moment and the $e^+ + e^- \rightarrow \mu^+ + \mu^-$ cross section.

As shown here muon-proton inelastic scattering would take place through the sum of two diagrams as follows:



One-photon exchange

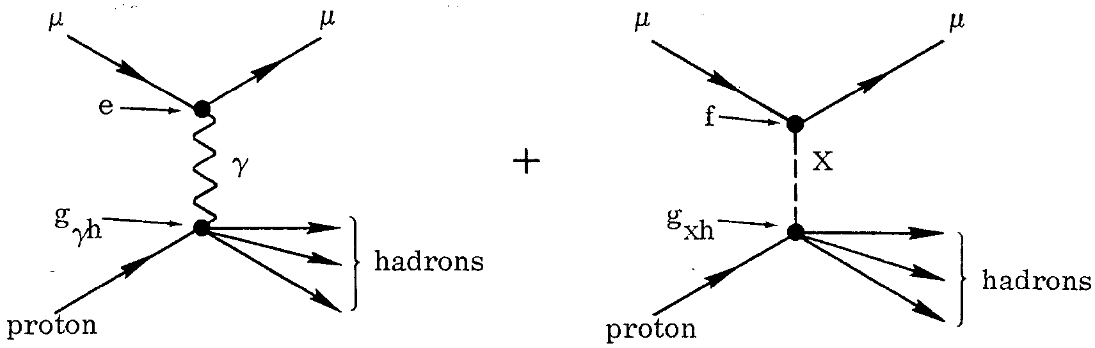
+



Special muon-hadron interaction

The second diagram would result in a difference between muon-proton and electron-proton inelastic cross sections, because only the first diagram would enter in electron-proton inelastic scattering.

As an example I shall assume that the muon interacts with the hadrons through the exchange of particle X with spin 1 and mass M_x.



One-photon exchange One-X exchange

Coupling constants are indicated in the diagrams; e is the electric charge. The coupling constants at the lower vertices are to be regarded only as very crude measures of the strength of the coupling of the virtual photon or the X particle to hadrons. Muon-proton inelastic scattering would take place through the sum of the two diagrams in the last figure. The second diagram would result in a difference between muon-proton and electron-proton inelastic cross sections, because only the first diagram would enter in electron-proton inelastic scattering. Then, to lowest order in the coupling constants,

$$\rho_{\text{inelastic}}(q^2, K) = \left[1 + \left(\frac{f}{e}\right)\left(\frac{g_{xh}}{g_{\gamma h}}\right)\left(\frac{|q^2|}{|q^2| + M_x^2}\right)\right]^2 . \tag{72}$$

Taking $(f/e)\ (g_{xh}/g_{\gamma h})$ to be real and negative, the best fit of our data[78] to this form gives

$$(f/e)\ (g_{xh}/g_{\gamma h}) = -.055 \pm .031 \qquad \text{and} \qquad M_x^2 = .184 \pm .443\ (\text{GeV}/c^2)^2 \tag{73}$$

The reader should be cautioned that this is only an example. The special muon-hadron interaction could involve many or all hadrons; and Eq. (72) and the fits in Eq. (73) would then just illustrate one of the simplest cases. In particular I do not mean to suggest that some undiscovered hadron of mass M_x is required for a special muon-hadron interaction.

A conventional speculation[91, 92] is that the X particle is some undiscovered heavy photon with e=f. But I prefer the speculation that the X particle is itself a hadron. More generally the X particle might be taken to represent the summation of the interaction of different kinds of hadrons with the muon. To estimate the present experimental limits on f, the coupling of the muon to the hadron X, I take $(g_{xh}/g_{\gamma h})^2$ to be the ratio of a typical hadron-hadron total cross section (30 mb) to the photon-proton total cross section (0.12 mb). Our muon-proton inelastic scattering measurements indicate b to be approximately .05. Then

$$f/e \approx .05/\sqrt{250} \approx 1/300 \quad . \tag{74}$$

Thus in this "X-hadron" model, the coupling of the muon to the hadrons is much weaker than the electromagnetic coupling. If such a coupling does exist, it can most likely be found only through the study of muon-hadron reactions. It will be difficult to find in purely electromagnetic experiments because the enhancement factor $(g_{xh}/g_{\gamma h})$ will not be available.

As an example, consider the effect of this "X-hadron" model on g_μ. The inclusion of X exchange in the g_μ calculation produces a modification given by Kobzarev and Okun[91] as

$$\frac{\Delta g_\mu}{g_\mu} = \frac{1}{3\pi}\left(\frac{f^2}{M_x^2}\right) m_\mu^2$$

which combined with the results of Picasso et al.[87] gives

$$\frac{f^2}{M_x^2} = (2.5 \pm 2.9) \times 10^{-4} \; (\mathrm{GeV}/c^2)^{-2}$$

or

$$\frac{f^2}{M_X^2} < 8.3 \times 10^{-4} \ (\mathrm{GeV}/c^2)^{-2} \tag{75}$$

with 95% confidence. Taking M_X^2 from Eq. (74) yields the limit

$$f/e < .15 \quad . \tag{76}$$

Equation (76) gives an upper limit to f/e which is much larger than the speculative estimate given in Eq. (74). The precision of the g_μ experiment would have to be improved by at least a factor of 1000 to test the estimate given in Eq. (74). Not only is this precision unobtainable with present experimental methods, but an effect of this very small size will be completely obscured by the expected strong interaction contribution[71,87] to g_μ. Similar remarks hold for the contribution of the "X-hadron" model to the process $e^+ + e^- \rightarrow \mu^+ + \mu^-$.[89,90] In the above we have assumed that the muon has a special interaction with hadrons and the electron is the conventional charged lepton with only electromagnetic and weak interactions. The contrary position can also be taken. Namely, there is a special electron-hadron interaction and the muon is the conventional charged lepton. The same analysis can then be pursued. The only difference is that the effect of the "X-hadron" model in purely electromagnetic interactions is even smaller.

F. Searches for Heavy Leptons in Charged Lepton-Proton Inelastic Scattering

Consider the sequence of reactions

$$e + p \rightarrow e^* + p \tag{77a}$$

$$e^* \rightarrow e + \text{other particles} \tag{77b}$$

or

$$e + p \rightarrow e^* + 2 \text{ or more hadrons} \tag{78a}$$

$$e^* \rightarrow e + \text{other particles} \tag{78b}$$

In the simplest inelastic scattering experiment, in which only the final electron is detected, reactions (77) or (78) would contribute to the total inelastic cross section, but the e* would not be detected. Similar considerations hold for muon initiated reactions. Therefore a comparison of electron-proton and muon-proton inelastic scattering is an indirect search for heavy leptons.

For example one may speculate,[93] that the explanation for $\rho_{inelastic}$ on the average being less than 1.0 is that the electron-proton inelastic scattering measurements include the production of the undetected e*. The most likely candidate[93] for such a speculation is a heavy excited electron, e*, with a mass greater than 1.4 GeV/c^2. This last condition is necessary to satisfy the electron-proton elastic scattering searches described in Section V.D. Of course, such an explanation for the deviation of the average value of $\rho_{inelastic}$ from 1.0 cannot be used to explain why the average value of $\rho_{elastic}$ also deviates from 1.0.

G. Present and Future Comparisons of Muon-Proton and Electron-Proton Inelastic Scattering, and of Muon-Proton and Electron-Proton Elastic Scattering

An experiment[94] in which both inelastic and elastic muon-proton scattering are being studied is now being conducted at the Brookhaven National Laboratory by a Columbia, Rochester, NAL, Rockefeller, Harvard collaboration.[94] They are using an incident muon momentum of about 8 GeV/c. Extensions of the experiment may include the use of higher momentum muons and nonhydrogenic targets. This experiment will allow a search to be made for heavy excited muons through the study of the momentum and angular spectrum of the recoiling proton.[67] It will also permit a new comparison to be made of muon-proton and electron-proton inelastic and elastic scattering.

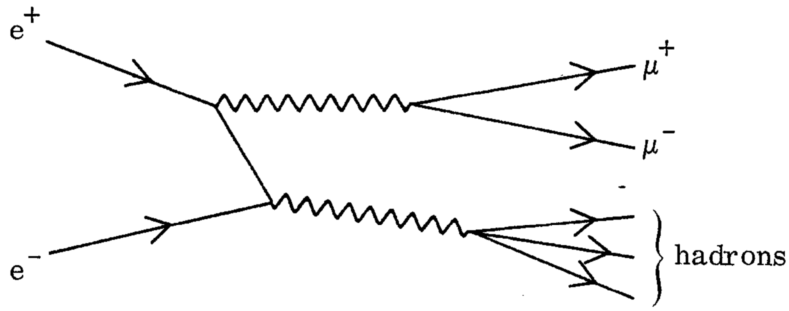
Very high energy comparisons of muon-proton and electron-proton inelastic scattering are now being contemplated[70] in future experiments at the National Accelerator Laboratory. If there are muon-electron differences which become more evident as $|q^2|$ increases, then such comparisons may be very fruitful. On the other hand, the normalization problems, which have limited past comparisons,[78] may be more severe at very high energies. Therefore if there are muon-electron differences of the types discussed in the previous two sections, which do not become more evident as $|q^2|$ increases, then these very high energy experiments may not provide the most sensitive comparison.

Because of this possibility, we are attempting to design at SLAC a new experiment to compare muon-proton and electron-proton inelastic scattering, in which careful attention is paid to the normalization problem. The completion of this design awaits among other things, final results from the BNL experiment discussed above.

The possibility also exists that the most sensitive way to search for a muon-electron difference is to study relatively low energy muon-proton and electron-proton elastic scattering where very precise measurements may be possible. Muon-proton elastic scattering experiments in the 100-500 MeV/c incident momentum range have been proposed, by P.A.M. Gram et al.[95] for the Los Alamos Meson Physics Facility. These experiments, which have not yet been accepted, would be used for a comparison with electron-proton elastic scattering. The theory of this comparison and some speculations on the possible results have been given by H. W. Fearing.[96]

H. Search for Anomalous Charged Lepton-Hadron Interactions Using Electron-Positron Colliding Beams

Finally I shall mention[93] a search we plan to undertake at SPEAR for anomalous muon-hadron interactions. We observe that muons and hadrons can only be produced in the same interaction at SPEAR through reactions like



The cross sections for reactions such as this one are smaller by a factor $\alpha^2 \approx 10^{-4}$ compared to the cross section for the production of hadrons alone. Therefore if we search for reactions in which hadrons and muons are produced in the same interaction, and if we find the cross section for such interactions to be larger than the very small estimate which has just been given, then we will have found an anomalous muon-hadron interaction. Of course we must be careful to eliminate the background of muons which come from pion or kaon decays, and therefore accompany events which are actually purely hadronic. We have chosen to search for the muon-hadron rather than the electron-hadron combination because the backgrounds are very severe for the latter combination.

With this final speculation I conclude this paper, although I am sure that many other speculations, and particularly many more fruitful speculations, can be made. But I hope I have made clear how little we know experimentally about heavy leptons and anomalous leptonic interactions; and I hope I have shown how much remains for us to investigate.

I am deeply indebted to J. D. Bjorken for many stimulating conversations on the subjects I have discussed in this paper.

APPENDIX

In this paper I use units in which $\hbar=1$ and $c=1$. Unless otherwise noted, energy is in GeV, momentum is in GeV/c and mass is in GeV/c^2. The charge on the electron is $e=\sqrt{4\pi\alpha}$ where $\alpha=1/137$.

I use the metric in which the square of a four-momentum vector P is $P^2 = M^2 = E^2 - (\mathbf{p})^2$.

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