SEARCH FOR HEAVY LEPTONS

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ABSTRACT

We describe experimental possibilities to check on the hypothesis that there are leptons with masses higher than that of the K meson. After a brief review of production and decay mechanisms for such heavy leptons, their predicted characteristics are used to evaluate various schemes for their detection. While clashing-beam facilities and high-intensity electron linacs appear most useful for some of these schemes, a particularly attractive experimental method may be exploited in the tagged photon facility to be built at the 200-GeV National Accelerator Laboratory.

I. INTRODUCTION

One of the major puzzles facing physicists today is the question: Why do we have two particles, electron and muon, each carrying its own distinctive additive quantum number (the "subleptonic charge"), each accompanied by its own neutrino but otherwise distinguished only by their masses?

In the absence of a satisfactory answer or speculation on this point, another question arises: If there is a sequence of independent leptons, why should it be confined to two members only? From hadron physics we are accustomed to sequences (or families) of particles which comprise more--sometimes many--members.

This question is equally difficult to settle, but we can try a speculative answer: Due to their small rest mass, the electrons cannot decay; the muons can decay only into electron and neutrinos--the subleptonic charge-conservation law demanding a three-body final state and therefore a slow decay. Were there, however, a heavier lepton, we might well have missed out on its detection: it could semileptonically decay into $\pi\nu$, $K\nu$, etc., depending on its rest mass. Especially at lower masses, these two-body decay modes may be faster than the leptonic ones. Furthermore, its weak interaction with other particles might very well have eluded our observation.

Let's assume that one (or more, for which case the same arguments may be repeated) further leptons of mass

$$m_\ell > m_K$$

exist (if $m_\ell < m_K$, the kaon would decay into it). Detection schemes then would rest on the following features:

1. The lepton ℓ, just like e, μ, carries its own distinctive quantum number L_ℓ; its decay products will always contain a neutrino with this quantum number. Leptonic decays will be into three-body final states; semileptonic decays will predominate at lower mass.

2. The lepton ℓ has subleptonic charge L_e or L_μ (maybe there is an alternating series). This would still lead to three-body leptonic final states but would make neutrino-less semileptonic decays possible, e.g.

$$\ell \rightarrow \pi e \text{ or } \pi\mu$$

$$\ell \rightarrow Ke \text{ or } K\mu.$$

Also possible is the radiative decay:

$$\ell \rightarrow e\gamma \text{ or } \mu\gamma.$$

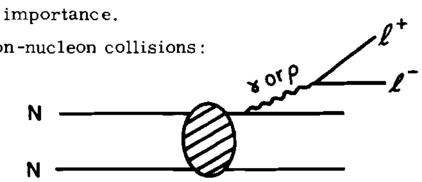
Experiments attempting to detect the existence of such hypothetical heavy leptons can therefore be categorized into those that make use of the existence of a new subleptonic charge, which must be conserved in the decay, and those that make use only of the leptons' mass and the distinctive kinematical features of their decay.

In this note, we briefly look into the various ways in which the existence of such heavy leptons can be experimentally investigated. As will be seen, several of the procedures suggested here could be successfully applied at the National Accelerator Laboratory's 200-400 GeV synchrotron.

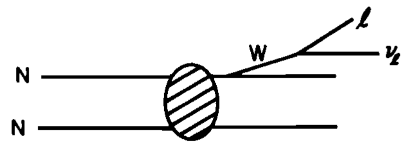
II. PRODUCTION MECHANISMS

Among the many possible production mechanisms, we shall mention only three which are of obvious importance.

1. From proton-nucleon collisions:

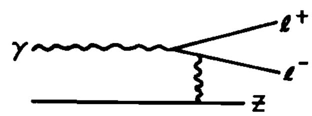


The usefulness of the diagram involving radiation of ρ production is hard to evaluate, since a recent experiment on high-mass μ pairs[1] has given results indicating a sizable continuum, but no peak. A possible signal of large-angle muons from ℓ decay would probably be drowned out. Similarly, the graph containing the vector boson W and its



subsequent decay into lepton and neutrino is likely to be difficult to detect (and can be evaluated only in a model-dependent way). Both of these diagrams (and many variations) are observable only by means of the detection of large momentum transfer μ's or electrons. Such measurements can be performed both at present proton machines and at the CERN proton storage rings.

2. From photon-nucleon collisions. The other plentiful particle source at our disposal is the electron accelerator. Either real or virtual photons, impinging on a high-Z target, will produce lepton pairs in the coulomb field of the nuclei. It will be seen that this appears to give the best signature for experimental investigation. This



cross section is strictly calculable for given lepton mass and momentum transfer; we shall have to assume that we can make use of known nuclear form factors. The form factors fall off rapidly with momentum transfer. The cross section turns out to be, for lepton masses of interest,

$$\sigma_{tot} \sim \int_{q_{min}}^{q_{max}} F^2(q)\sigma(q)\, dq,$$

$\sigma(q)$ is the pair production cross section, $F(q^2)$ is the form factor; the upper limit of the integral may be taken as some value of q where the form factor depresses the integrand seriously.

We give some values of production cross section in nuclei in Table I: as examples for high-Z targets, we picked nickel (Z = 27) and lead (Z = 82). The last line gives, for a comparison with "background" reactions, the total γp-hadronic cross section which is roughly

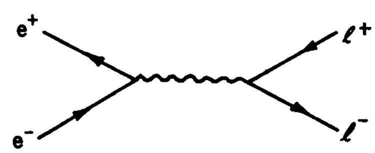
$$\sigma_{tot}(\gamma p \rightarrow \text{hadrons}) = 90\,\mu b \times A^{0.84},$$

Table I. Heavy Lepton Production Cross Sections at E_{in} = 25 GeV for Various Lepton Masses, in μb/nucleus[4].

Mass	σ(Ni)	σ(Pb)
0.7 GeV/c^2	4.3×10^{-2}	1.5×10^{-1}
1.0 GeV/c^2	2.1×10^{-3}	4.6×10^{-2}
1.2 GeV/c^2	3.0×10^{-4}	6.5×10^{-4}
$\sigma_{tot}(\gamma p \to \text{hadrons})$	2.75×10^{3}	6.88×10^{3}

where the A dependence indicates that we are dealing predominantly with coherent production. Counting rates can be obtained from these numbers for any given branching ratio, and for any particular set of kinematical parameter. With SLAC fluxes, extremely thin high-Z target foils will still yield sizable production rates. Small photon fluxes will have to be, at least partially, compensated for by thicker production targets and larger solid angle detection devices.

3. The third production mechanism is closely related to photoproduction:



This is the mechanism which will be looked for at the clashing beam electron-positron machines. The predicted cross section is, for a heavy lepton of mass ~1 GeV/c^2, on the order of 10^{-32} cm^2 under favorable conditions (see below).

III. DECAY MODES, LIFETIMES

The principal decay modes of a heavy lepton are, for the case where the lepton has its own subleptonic charge:

a) $\ell \to e\nu\bar{\nu}$

b) $\to \mu\nu\bar{\nu}$

c) $\to \pi\nu$

d) $\to K\nu$

e) $\to \rho\nu$

$\to$ (hadrons + leptons).

In addition, heavy leptons having the same subleptonic charge as either electron or muon can decay according to

f) $\ell \to e$ (or μ) + hadrons

g) $\to e$ (or μ) + photon.

It is clear that the radiative decay (g) would be much faster than the weak decay. It therefore hardly lends itself to an investigation of the existence of ℓ: the accompanying photon could always be radiatively produced in the high-Z target itself.

We can calculate the decay widths (in the rest system of the ℓ). For a), b)

$$\Gamma_{\ell \to \mu} \approx \Gamma_{\ell \to e}. \tag{1}$$

We assume $m_\ell >> m_e$ and $m_\ell >> m_\mu$, then use the same expression as for μ decay:

$$\Gamma_{\ell \to e, \mu} \frac{G^2 m_\ell^5}{192\,\pi^2}. \tag{2}$$

For c), d) (semileptonic decays), we can calculate the matrix elements

$$< \pi \,|J_\mu|\, 0>, \; <K \,|J_\mu|\, 0>.$$

Assuming we can take the pion form factor as known, and a K form factor roughly equal to F_π (as suggested by PCAC), and taking for J_μ the currents including the Cabibbo angle θ_c, we get

$$\Gamma_{\ell \to \pi} = \frac{G^2}{16\,\pi} \; m_\ell^5 \cos^2 \theta_c \frac{F_\pi^2}{m_\ell^2} \left(1 - \frac{m_\pi^2}{m_\ell^2} \right) \tag{3}$$

$$\Gamma_{\ell \to K} = \frac{G^2}{16\,\pi} \; m_\ell^5 \sin^2 \theta_c \frac{F_K^2}{m_\ell^2} \left(1 - \frac{m_K^2}{m_\ell^2} \right). \tag{4}$$

Knowing the Cabibbo angle, we can see that the ratio

$$\frac{\Gamma_K}{\Gamma_\pi} < \frac{\sin^2\theta_c}{\cos^2\theta_c} \approx 0.075 \tag{5}$$

indicates only a small K admixture, particularly if we also take the mass ratios m_π/m_ℓ and m_K/m_ℓ into account [cf. Eq. (3) and Eq. (4)].

Table II gives a summary of lifetime and branching-ratio information.[4]

Table II. Lifetimes and Branching Ratios.

$m_\ell (\mathrm{GeV}/c^2)$	τ_ℓ (sec)	$\Gamma_\mu/\Gamma_{tot} = \Gamma_e/\Gamma_{tot}$	Γ_π/Γ_{tot}	Γ_ρ/Γ_{tot}
		(in percent)		
0.7	3.3×10^{-11}	19.5	61	0.0
1.0	7.1×10^{-12}	27.7	42	2.4
1.5	6.3×10^{-13}	36.0	24.5	3.5
2.0	3.1×10^{-14}	39.0	14.8	7.2

This table neglects, according to Eq. (5), the K contribution; the ρ contribution is added simply to illustrate the level at which other hadronic states may appear, and all other such states were disregarded.

IV. POSSIBLE EXPERIMENTS

A. Pair Production

Probably the most obvious experiment to be performed on the production of heavy leptons is the pair production from an e^+e^- initial state

$$e^+e^- \to \ell^+\ell^-, \tag{6}$$

which is supposed to proceed through a one-photon intermediate state.

This experiment can be performed at clashing beam facilities and is in active preparation at the 2×1.5 GeV storage ring Adone in Frascati, Sicily[2]; accordingly, leptons of masses up to 1.5 GeV/c^2 can be investigated there.

The principal experimental handle is this: Two leptons, produced with equal and opposite momenta in center-of-mass and laboratory frame, will decay within a very short distance from the point of their origin (cf. Fig. 1). In a large solid-angle

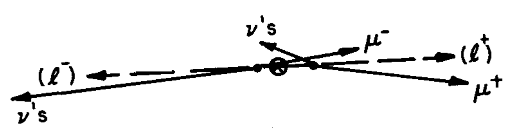


Fig. 1.

detector around the interaction region, one therefore looks for non-collinear muon tracks.

There are error possibilities, of obvious origins. Also, tracks that might be taken for good events of this type may well come from intermediate bosons. (Expected cross-section limits at Frascati, for $m_\ell \approx 1$ GeV, are at the 1 to 10 nb level.[2]

B. Production in Nucleon-Nucleon Collisions

This production scheme, which would lead, as an experimentally distinguishing feature, to large-momentum-transfer muons beyond the angular range of high-energy muons produced by μ pair production, is fraught with practical difficulties.

A very intense proton beam is needed, and there will always be a very noticeable muon background all around the proton beam area; shielding is very complicated, and an exact determination of the origin may be needed.

Furthermore, as we mentioned above, Lederman et al.[1] recently observed an unexpectedly large number of high-mass muon pairs in 29 GeV/c pN collisions at the AGS in Brookhaven: a signal for our experiment well may be drowned out by this smooth continuum of μ pairs.

A number of decay processes can in principle contribute to the detection of large-momentum-transfer muons. In particular, the intermediate vector boson could cause such muons to exist. In this instance, however, the "positive muon excess" characteristic of some boson production mechanisms[3] gives us a handle to discriminate between muons from ℓ's and from W decays. We do not believe this search to be particularly promising and will forego further discussion.

C. Photoproduction of Heavy Lepton Pairs with Maximum Intensity Beams

This experiment makes use of the full beam power of, preferably, an electron accelerator. The scheme is illustrated in Fig. 2. An intense electron beam impinges on a high-Z target; the bremsstrahlung photons produce pairs of leptons (e^+e^-, $\mu^+\mu^-$, $\ell^+\ell^-$) and many hadrons. Immediately downstream, a high-Z shield absorbs all hadrons--in particular, π and K mesons will pass through many nuclear interaction lengths before having a chance to decay weakly. Muons similarly are slowed down. Of the decay products, μ's, electrons, or hadrons will be absorbed in the thick shield, but the heavy lepton's associated neutrino, ν_ℓ, will be detectable on the far side of the heavy shield.

Crude scintillator hodoscopes and thick-plate spark chambers, with appropriate vetoing devices against cosmic-ray backgrounds, will be triggered by charged products of the secondary reaction

$$\nu_\ell + Z \rightarrow Z' + \text{hadrons, leptons.} \tag{7}$$

A detailed search for distinctive signatures can tell the difference between contaminating muon and electron neutrinos; this search will be easier if the mass of the heavy lepton is light enough (< 1 GeV/c^2), so that the hadronic decay modes prevail (see Section III).

D. Pair Production with Spectrometer Detection of Downstream Decays

Although the heavy lepton lifetime can be expected to be in the 10^{-11}-10^{-12} sec range, sufficiently energetic heavy leptons will still travel several centimeters before decay. The method of detection discussed in this section consists of observing the decay electron (or muon) from these downstream decays at a sufficiently wide angle to be sure that it did not originate in the target. Great care must be given to the design of a spectrometer to minimize the background from slit scattering and aberrations, but it appears possible to achieve a useful arrangement.

We note several independent checks which must be satisfied by a true heavy lepton signal. First, there is a strong correlation between the decay electron momentum spectrum and the decay angle. This is particularly so because the heavy leptons which contribute are highly relativistic (to get downstream) and we are observing decays at a "large" angle. Recall that at 90° in the lab the derivative $dp/d\theta$ is singular. Secondly, the distribution of decays in space can be measured (most conviently by moving the target) and is a predictable function once the mass is known. In short, the joint distribution function $d^3N/dp_e d\theta_e dz$ depends only on one unknown parameter, the mass of the lepton--a highly constrained situation.

The event rate for such an experiment is "low" for several reasons. First, only the highly relativistic heavy leptons are useful. Second, the spectrometer has of necessity a limited acceptance. Finally, the region directly ahead of the target is not useful because the decay electrons cannot be separated from electrons produced in the target. Estimates indicate that such an experiment may well be feasible at SLAC but probably would not be feasible at NAL.

E. Photon Tagging

Last, a very promising method of detecting heavy lepton production makes use of the photon tagging method to compare the invariant mass of detected pairs with the incident photon energy. Figure 3 illustrates this scheme: photons of known energy produce charged particle pairs in a high-Z target no more than ~5 mm thick. This production target is placed inside a wide-gap or streamer chamber so that emergent tracks can be followed for a considerable length (at least 20 cm).

Heavy leptons of sufficiently high γ values will often yield recognizably long tracks in the chamber before decaying; their decay shows up as (at least) a kink in the track. The chamber is either immersed in a magnetic field or followed by one, so that the momenta of charged decay particles can be measured. A subsequent set of thick-plate spark chambers either detects a nuclear interaction (if the decay was hadronic), an electron shower, or a long muon track, for leptonic decays. The most distinctive signature is supplied by the process

$$\gamma Z \to Z\,\ell^+\ell^-\ (\ell^+,\ \ell^- \to \mu^+,\ \mu^- + \text{neutrinos}), \qquad (8)$$

where the streamer chamber and the downstream range chambers will detect a muon pair of total energy considerably lower than the incident photon energy. If the kinks due to the leptons' decay and the momentum measurements in the streamer chamber are sufficiently accurate, subsequent electron showers will give a comparable signature for the process

$$\begin{aligned} \gamma Z \rightarrow Z\, \ell^+ \ell^- \; &(\ell^+,\ \ell^- \rightarrow e^+,\ e^- + \text{neutrinos}) \\ &(\qquad\quad \rightarrow e^\pm,\ \mu^\mp + \text{neutrinos}) \end{aligned} \tag{8'}$$

V. CONCLUSION

We have indicated a number of possible experimental methods that may prove useful in a search for the conjectured existence of heavy leptons. Only one such possibility (C) makes use of the assumption that this lepton may carry its own additive quantum number, L_ℓ.

Methods (A) and (B) are most easily applied at clashing electron and proton beam facilities, respectively; method (C) is a natural for a high-current electron machine; (D), because of the small solid angle subtended by the spectrometer, would need a high photon flux to generate some admissible counting rates; (E) looks like an interesting project to be taken up by NAL in its projected electron-photon beam, since the large-solid-angle detector can make up for the low beam intensity to a certain extent. We therefore suggest that this method be investigated in a more detailed way at NAL, should the lepton question remain an open one by the time of its operation.

Methods (B) and (C) are not necessarily excluded at high-energy proton synchrotrons, although well down on our preference list. Principal contaminant for an assumed heavy lepton in most detection schemes would be the other ghost in the haunted house of the weak interactions, the intermediate boson. Its decay into lepton pairs only, and lifetime considerations provide some handle for proper discrimination. Obviously, background problems have to be studied in the framework of individual detection schemes and are beyond the scope of this note.

REFERENCES

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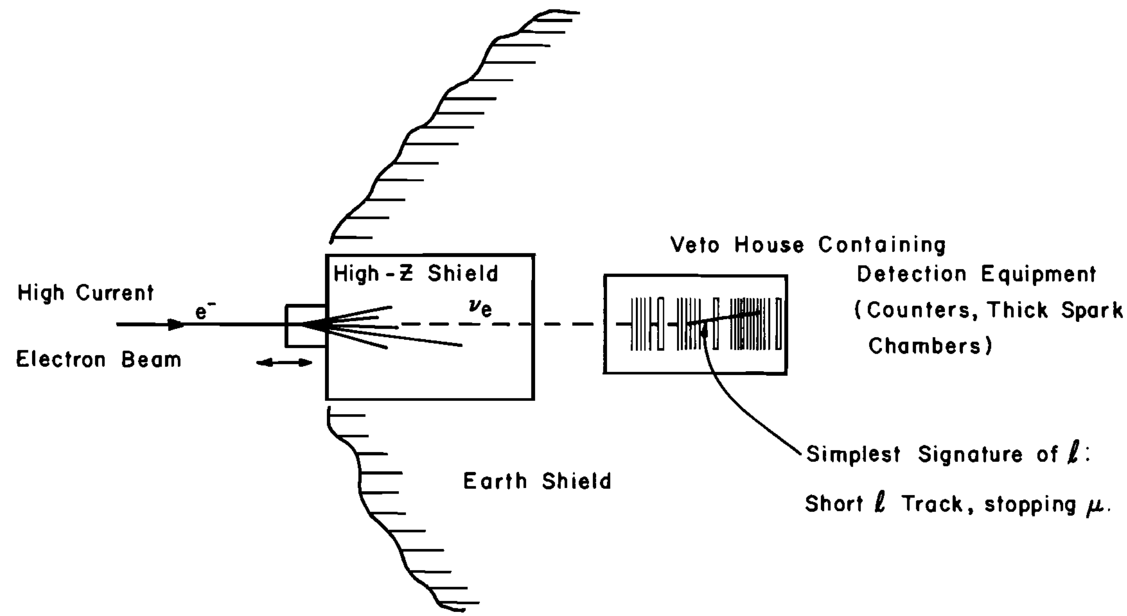

Fig. 2. Schematic layout of detection method (c), using high-current electron linac. Signature is provided by neutrino-induced tracks in well-shielded detection house.

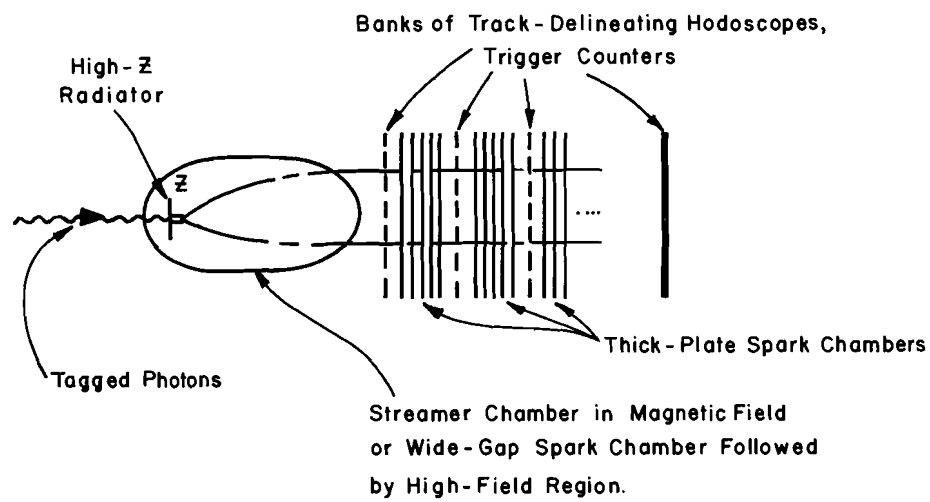

Fig. 3. Schematic layout of experimental method (e), using photons of known energy and a large solid-angle detection device. Signature is provided by kinks in the tracks.