[6]E. Anderson *et al.*, Phys. Rev. Lett. 22, 1390 (1969).

[7]Logarithmic dependence of $d\sigma/du'$ on $u'$ has been observed in Reaction (2) (Ref. 6); i.e., $d\sigma/du' \simeq \exp(Bu')$, where $B \simeq 2.6$ for background events and $B \gtrsim 4$ for resonances. Consequently, a $u'$ cut is expected to enhance resonance states relative to the background.

[8]The Lorentz-invariant phase space is weighted by the square of the matrix element proportional to $\exp(-B\sum p_{\perp,i}^2)$ where $i$ extends over all final-state particles. The value of $B$ is obtained by comparing $p_{\parallel}$ and $p_{\perp}$ distributions in the data, for all four-constraint final states, with the predicted distributions obtained with the Monte Carlo program. A value of $B = 2.5$ represents a good average value to describe most of the qualitative features of the data.

[9]Using $d\sigma/du' \simeq \exp(4u')$ for backward resonance production (see Ref. 7), we estimate that in accepting protons within 50 mrad of the beam direction, about 70% of possible resonances in this channel are included.

# Test for the Existence of Effectively Stable Neutral Heavy Leptons

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I propose a test for the existence of stable or unusually long-lived neutral heavy leptons using a beam-dump experiment with precise timing. The technique can also be used to measure the lepton mass. Several reactions which can help to determine the couplings of such a lepton and can serve as new probes of hadronic structure are discussed.

An old and intriguing question in particle physics is the following: Are the only stable leptons the ones of which we are already aware, namely $e$ and also , if massless, $\nu_e$, $\nu_\mu$, and $\nu_\tau$, or are there others? From recent work on unified models of weak and electromagnetic interactions[1] there is indeed some reason to think that a stable neutral massive lepton may exist. Such an absolutely (or effectively) stable lepton will be denoted $E^0$. In this paper I shall propose a model-independent test for the existence of stable or unusually long-lived $E^0$'s. I shall also outline the features of several reactions involving such leptons.

The test which I propose utilizes a beam dump followed by a massive electronic target calorimeter with muon and, ideally, also electron spectrometers. At present it is, we believe, the most, and probably the only, practical way to search for (effectively stable) $E^0$'s. The crucial aspect of the experiment is the use of timing to an accuracy of ~1 nsec in order to discriminate between the arrival of massless and massive neutral leptons and to select the latter. Beam-dump experiments have been carried out in the past as a means of searching for a leptonic signal from short-lived hadrons, or for unstable leptons[2]; however, they have not used timing methods as proposed here. In particular, the searches of Ref. 2 for the decay $L^0 \to \mu^\pm\ (e^\pm) + \pi^\mp$ do not bear on my suggested test, which is sensitive to longer-lived leptons. Precise timing has been used previously in the experiment of Alspector *et al.*[3] to measure the difference in $\mu$ and $\nu_\mu$ velocities, but this was not a beam-dump experiment and hence was not optimized to search for $E^0$'s.

A beam-dump experiment is uniquely sensitive to the leptonic decay products of short-lived hadrons containing heavy quarks. These decays will yield $\nu_e$, $\nu_\mu$, and, for sufficiently heavy hadrons, $\nu_\tau$. They may also yield stable or long-lived neutral heavy leptons. This possibility is present, independent of any specific models; however, in particular, the SU(3) ⊗ U(1) theory[1] predicts that the lightest of the set of quarks heavier than $c$, viz. $Q = t$ or $b$, will decay 100% of the time into $\overset{(-)}{E}{}^0$'s: $t \to (d \text{ or } s) + (e^+ \text{ or } \mu^+) + E^0$ or $b \to u + (e^- \text{ or } \mu^-) + \bar{E}^0$. The production of heavy hadrons is Zweig suppressed relative to light hadrons; the suppression factor is roughly $10^{-3}$ for charm and correspondingly smaller for heavier quarks. This will be reflected in the $\overset{(-)}{E}{}^0$ flux. However, with the timing discrimination there are essentially no significant backgrounds to our suggested search; in particular $\overset{(\rightarrow)}{\nu}_e$, $\overset{(\leftarrow)}{\nu}_\mu$, (massless) $\overset{(-)}{\nu}_\tau$, and muon halo do not constitute backgrounds. Thus the test is sensitive to a very small signal.

The proposed test makes crucial use of the rf structure of a pulse of protons from the accelerator. At Fermilab, a pulse consists of a large number of individual bunches of protons, each of width ~1 nsec, separated by 18.8 nsec. This rf structure is preserved by neutrinos from the dump, given the existing upper bounds on their masses[4,5] and the fact that the path length $l \lesssim 1$ km. A timing signal from the accelerator can be used to determine the time at which the neutrinos will arrive at a particular point in the detector. If these points were the same for a massless and massive lepton then the latter would lag behind the former by $\Delta t = (l/c)(\beta^{-1} - 1)$. These leptons will in general interact at different points, but this can be taken into account in measuring the relative flight times. The two main sources of error in the time measurement relative to the true time are (1) the finite width of the proton bunches and (2) the measurement error of the longitudinal point of interaction in the detector: together, these produce a total error estimated to be ~1.5 nsec. This in turn determines the maximum value of $\beta$ which can be distinguished from unity; it is given by $\beta^{-1} - 1 = \epsilon$, where $\epsilon \simeq 0.5 \times 10^{-3} [l/(1\text{ km})]^{-1}$. This corresponds to a minimum value of $\gamma^{-1} = m_E/E$ [where $E$ ($m_E$) is the $E^0$ energy (mass)] which can be distinguished from zero: $\gamma^{-1} = [2\epsilon(1+\epsilon/2)]^{1/2}/(1+\epsilon)$. In some of the $\overset{(-)}{E}{}^0$-induced reactions (type-1 charged current; see below) it is possible to determine $E$ with an accuracy comparable to that in a regular neutrino experiment. Together with the measurement of $\gamma$ from $\Delta t$, this enables one to compute the $E^0$ mass. To the extent that some energy is missed, $E_{\text{vis}} < E$ and hence $(m_E)_{\text{vis}} < m_E$; thus $m_E \simeq [(m_E)_{\text{vis}}]_{\max}$. Taking $E \simeq 20$ GeV as a rough value below which the $\overset{(-)}{E}{}^0$ flux would be significantly reduced, we find, finally, that the proposed test is capable of discovering an $E^0$ of mass $m_E \gtrsim 0.6$ GeV (or even less if $l > 1$ km). For reference, the mass of an absolutely stable $E^0$ is bounded according to $m_E \lesssim 40$ eV or $m_E \gtrsim 1-4$ GeV.[6]

In order to use this timing method to assign an approximate value of $\gamma$ to the delayed leptons, one must know from which bunch of protons they came. This requires that the time delay $\Delta t$ be less than the 19-nsec separation between these bunches and consequently sets a lower bound on $\beta$ and $\gamma$ and an upper bound, for a given $E$, on the mass $m_E$ which can be observed by the experiment. To sample leptons with smaller $\gamma$'s within the required maximum time delay one could reduce $l$. We stress, however, that the observation of a delayed lepton signal would represent a major new discovery in weak interactions, even if it were not possible to assign a definite $\gamma$ and approximate $m_E$ to it.

The designation "effectively stable lepton" includes, of course, an unstable lepton which decays with sufficiently long lifetime $\tau$ that $\gamma\beta c\tau > l$. The discovery of such a lepton would in itself be almost as exciting as that of a truly stable lepton, for the following reason. A typical decay rate of a massive lepton $L$ is $\Gamma \sim \lambda N G_F{}^2 m_L{}^5/193\pi^3$, where $N$ denotes the number of available decay channels kinematically unsuppressed by phase space and $\lambda$ represents a possible dynamical suppression factor. In order that $\gamma\beta c\tau > l$ for $l \sim 1$ km, we find that $\lambda \lesssim (2\times 10^{-6})\gamma\beta[m_L/(1\text{ GeV})]^{-5}$. Thus although a positive delayed lepton signal would not definitely indicate the existence of a stable lepton, it would at least indicate one whose decay rate is suppressed far below its natural weak level. A second comment concerns Higgs scalar bosons. Since such bosons have semiweak decay rates, they will decay long before reaching the detector, even for Higgs mass values several orders of magnitude below the level which could be discerned experimentally.

The delayed arrival of the $\overset{(-)}{E}{}^0$'s can be established by the use of a target-calorimeter muon spectrometer similar to the ones which have been employed in high-energy counter neutrino experiments at Fermi National Accelerator Laboratory (FNAL) and CERN. The interaction of the $\overset{(-)}{E}{}^0$'s with the target will be signaled by hadronic energy deposition together, in some of the charged-current (CC) reactions, with an outgoing $e$ or $\mu$. Most conventional counter experiments cannot distinguish an electron from a hadronic shower, so that such CC events, as well as those in which a heavy charged lepton is produced and decays into an $\overset{(-)}{E}{}^0$ plus hadrons, would appear as neutral-current (NC) events. A bubble chamber could not be used for our proposed test because it is incapable of the precise nanosecond timing required. However, counter experiments which have been built or proposed to search for leptonic neutral-current reactions would be able to achieve such precision of timing and also detect the scattered electron in delayed lepton events. In passing, we note that a similar beam-dump experiment with precise timing can be used to search for effectively stable charged heavy leptons (denoted $E^-$).

We proceed to consider the various $\overset{(-)}{E}{}^0$-induced reactions. The kinematics of these reactions is qualitatively new since they involve a heavy incident lepton. In contrast to high-energy CC muon reactions, which are helicity suppressed if $\mu$ couples only via weak charged currents of a single (left-handed) helicity, $\overset{(-)}{E}{}^0$ reactions will not be similarly suppressed, even in a theory such as that of Ref. 1, where $E^0$ has only right-handed weak couplings. This is a consequence of the greater mass of the $E^0$ and the much greater importance of multipion semileptonic, as opposed to two-body leptonic, decay modes of heavy mesons. Moreover, the lightest spin-$\frac{1}{2}$ $Q$-flavored baryon will probably have only weak decays since presumably $m_B - m_M < m_N$, where $N$ ($M$) denotes nucleon ($Q$-flavored pseudoscalar meson); these will serve as another source of $\overset{(-)}{E}{}^0$'s with arbitrary helicities.

Among unstable but long-lived neutral heavy leptons an especially interesting possibility is that the Perl neutrino $\nu_\tau$ is not massless, or, more precisely, that $m_{L^0} \neq 0$, where $L^0$ is the mass eigenstate corresponding to $\nu_\tau$ in the notation of Ref. 5. If $l \lesssim 1$ km, then, given the present mass limit $m_{L^0} < 0.6$ GeV,[4] the proposed test would not be able to distinguish such a massive lepton from a massless one; however, for $l \gtrsim 1$ km this would be feasible.[7] With these values of $m_{L^0}$ and $l$, together with the factor $\gtrsim 3\times 10^2$ suppression in the $L^0$ decay,[5] it would appear stable.

It is general property of any model with a stable $E^0$ that in the reaction $\overset{(-)}{E}{}^0 + T \to L + X$, where $T$, $L$, and $X$ denote, respectively, the target particle, scattered lepton, and the other particles comprising the final state, it is necessary that $m_E \leq m_T + m_L + m_X$. Hence inclusive semileptonic CC $E^0$-induced reactions must involve the production of (1) a heavy lepton, (2) a heavy quark, or (3) both (1) and (2). The dominant elementary CC type-1 (CC-1) reactions are probably the most amenable to experimental study. In the SU(3) $\otimes$ U(1) model they include $E_R^0 + d_R \to l_R^- + t_R$ and $\bar{E}_R^0 + u_L \to l_R^+ + b_L$, where $l = e$, $\mu$, and the subscripts refer to chiral components. By measuring $\gamma$, the energy $E'$ and scattering angle $\theta$ of the $l^\pm$, together with the hadronic energy deposition $E_H$, one can fully reconstruct the kinematical variables for this type of reaction: $E' + E_H = E$ (really $E_{\rm vis}$), $m_E = \gamma^{-1}E$, $\nu = E - E'$, and $q^2 = m_E^2 - 2E'(E - |\vec{p}_E|\cos\theta)$.

The new feature of these reactions is that $q^2$ can be timelike (positive); $(q^2)_{\max} \lesssim m_E^2$. If most of the square of the center-of-mass energy $s$ is provided by $m_E^2$, then most of the physical region has $q^2 > 0$. With these reactions one can thus probe hadronic structure in a kinematic region never before accessible to scattering (as opposed to annihilation) reactions. Because heavy-quark production occurs, the cross section exhibits nonscaling threshold effects; these can be incorporated by the use of a smeared threshold factor $\theta(W - W_Q)$, where $W$ and $W_Q$ are the invariant hadronic mass and its minimum value for $Q$ production, and by the use of an effective scaling variable[8] $\xi$, which is equal to the momentum fraction of the struck quark: $\xi \simeq (-q^2 + m_Q^2)/2m_N\nu = x + m_Q^2/2m_NE_y$, where $x = -q^2/2m_N\nu$, $y = \nu/E$, and $m_N$ ($m_Q$) is the nucleon (heavy-quark) mass.

The differential cross section for CC-1 reactions with incident $\overset{(-)}{E}{}^0$'s which have the favorable helicity to interact via a chiral leptonic vertex is

$$\frac{\partial^2\sigma}{\partial\xi\partial y} = r\,\frac{G_F^2 m_N E}{\pi\beta_E}\left\{\left(xy^2 + \frac{y(m_E^2 + m_l^2)}{2m_NE}\right)F_1 + \left(1 - y - \frac{2m_NExy + m_E^2 + m_l^2}{4E^2}\right)F_2 \pm y\left[x\left(1 - \frac{y}{2}\right) + \frac{m_E^2 - m_l^2}{4m_NE}\right]F_3 + \frac{1}{2m_NE}\left[xy(m_E^2 + m_l^2) + \frac{(m_E^2 - m_l^2)^2}{2m_NE}\right]F_4 + \left(\frac{1}{2m_NE}\left[m_E^2(1-y) - m_l^2\right]\right)F_5\right\}, \qquad (1)$$

where $r$ represents a scaling factor to take into account the difference in effective coupling strength of gauge bosons which mediate the reaction, and for generality the mass $m_l$ of the scattered lepton is retained. The CC-1 cross section for a particular experiment is the weighted sum of Eq. (1) and the contribution from wrong-helicity $\overset{(-)}{E}{}^0$'s (which vanishes), weighted according to the polarization state of the incident $\overset{(-)}{E}{}^0$'s at a given energy. The $F_i(\xi, Q^2)$ are the structure functions for the relevant (presumably isoscalar nucleon) target, and the $\pm$ sign for the $F_3$ term corresponds to like and opposite lepton and quark helicities. Using the parton-model relations $F_2 = 2\xi F_1$, $\xi F_3 = F_2$, $F_4 = 0$, and $\xi F_5 = F_2$ in Eq. (1), one finds that the new term proportional to $m_E^2$ in the curly brackets is $(m_E^2/4m_NE)[(2 - y \pm y)/\xi - m_N/E]$. If $m_E^2 \gtrsim 2m_NE$, this term significantly changes the behavior of the cross section, especially at small $\xi$. In the SU(3)$\otimes$U(1) model $r = \cos^2\beta$ ($\sin^2\beta$) for $\overset{(-)}{E}{}^0 + N \to e^\pm$ ($\mu^\pm$) $+ X$, where $E_R^{0\prime} = \cos\beta E_R^0 + \sin\beta M_R^0$ and $M_R^{0\prime} = -\sin\beta E_R^0 + \cos\beta M_R^0$ are the gauge-group eigenstates, and in Eq. (1) the upper sign applies for both $E^0$ and $\bar{E}^0$ reactions.

If $m_E > m_Q$ (but still less than the mass of any possible decay state) then $\xi$ can vanish and become negative. Since for a stable $E^0$, $m_E$ can never be much larger than $m_Q$, $-\xi$ is limited to small values, and since $(q^2)_{\max} = m_E^2$ corresponds to small $E'$, the events with $\xi < 0$ will be hard to observe experimentally. Nevertheless, they do enable one in principle to measure the structure functions in the new region of negative $\xi$. Moreover, in the case of a long-lived $E^0$, it is possible that $m_E \gg m_Q$ ($Q$ could be a light quark) and $-\xi$ could be of order unity. The singularities at $\xi = 0$ in the cross section expressed in terms of $F_2$ are only apparent since neither the analysis of Ref. 8 nor the parton-model relations used above are applicable at $\xi = 0$. The heavy quark produced in (stable $E^0$) CC-1 reactions has a significant semileptonic branching ratio. Accordingly, one expects dilepton events of the form $\mu\bar{\mu}$, $\mu\bar{e}$, $e\bar{\mu}$, and $e\bar{e}$.

Type-2 CC reactions also occur in the SU(3) $\otimes$ U(1) theory, via exchange of a regular $W$ boson; the elementary transitions are $E_R^0 + d_L \to L_R^- + u_L$ and $\bar{E}_R^0 + u_L \to L_R^+ + d_L$, where $L^- = E^-, M^-$. These reactions can be observed by the $\mu$ which may occur among the decay products of the $L^-$. If the $L^-$ decays into $E^0$ (or $e$, in a conventional counter experiment) plus hadrons, then the event will appear to be an NC event. The $y$ and $y_{\rm vis}$ distributions will be shifted toward smaller and larger values of $y$ and $y_{\rm vis}$, respectively. The differential cross section is given by Eq. (1) with $m_l = m_E$- or $m_M$- and $\xi = x$. In the theory of Ref. 1, $r = \cos^2\beta$ ($\sin^2\beta$) for $\overset{(-)}{E}{}_R^0 + N \to E_R^{\pm}$ ($M_R^{\pm}$) $+X$, and the lower (upper) sign for $F_3$ applies for incident $E^0$ ($\bar{E}^0$). The CC-2 reactions in which $L^- \to (e^- \text{ or } \mu^-) + \cdots$ can be distinguished on a statistical basis from CC-1 reactions because in the former (latter) (1) the $e$ or $\mu$ arises from $L^-$ decay (is produced directly); (2) $y$ is small (large); and (3) $W > m_N$ ($W > W_Q \gtrsim 5m_N$). Further, CC-2 reactions yield dilepton and trilepton events in which the leptons emerge from the leptonic vertex, in contrast to charm or CC-1 dileptons. The CC-2 and CC-1 dileptons can be distinguished by their different energy, opening-angle, and azimuthal-angle distributions.

As is evident, the CC reactions of $\overset{(-)}{E}{}^0$'s will in general involve gross $\mu$- and $e$-type lepton-number nonconservation. This could be established experimentally by observing both $e$ and $\mu$ produced directly by $\overset{(-)}{E}{}^0$ in CC-1 reactions. However, to do this it would be crucial to show that the $e$ and $\mu$ did not arise from $L^-$ decay in CC-2 processes.

Although the (apparent) NC signal is an important test for delayed leptons, the experimental study of $\overset{(-)}{E}{}^0$-induced NC reactions will be difficult because, in contrast to regular neutrino experiments, it is not possible to select $E^0$'s or $\bar{E}^0$'s by the usual meson-focusing methods, and hence the measured cross section will represent in general an unknown mixture of $E^0$ and $\bar{E}^0$ contributions. A more detailed discussion of these and the other $\overset{(-)}{E}{}^0$-induced reactions will be given elsewhere.[7]

Finally, we note that the production and interaction of (necessarily rather light) $\overset{(-)}{E}{}^0$'s may contribute in part to the apparent excess of $e^{\pm}$ and $\mu^{\pm}$ events observed in recent CERN and FNAL beam-dump experiments.[9] This possibility can be decisively tested by the timing method discussed above

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