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ABSTRACT

We report a null search for neutral heavy leptons produced unaccompanied by muons in 400 GeV/c proton-nucleon collisions in a magnetized beam-dump and decaying in vacuum downstream. The upper limit on σB for L^o's with Feynman $x \gtrsim 0.2$ and $\theta_{lab} \lesssim 10$ mr with branching ratio B into two charged particles is $\sigma B \lesssim 2.8 \times 10^{-35}$ cm^2/nucleon at the 90% confidence level for masses below 1.0 GeV/c^2 and lifetimes between 10^{-10} and 10^{-8} seconds.

Extensive searches for the existence of heavy leptons ($L^{\pm}, L^{o}$) have been made in high-energy proton collisions,[1,2] in neutrino reactions,[3] and in $e^{+}e^{-}$ annihilations.[4] Inconclusive signals for their production have been reported in the literature.[5-7] If neutral heavy leptons are the lightest members of their family, then they may decay into $\mu^{\pm}(e^{\pm})$ + hadrons $^{\mp}$ and this decay may be very slow. This is plausible, because the success of renormalizeable gauge theories of weak and electromagnetic interactions strongly suggests that muon-number conservation might not be a fundamental symmentry law of nature.[8,9] Thus, processes such as $\mu \rightarrow e + \gamma$ would not be forbidden, but would be highly suppressed. Similarly, the decay of a neutral heavy lepton might also be greatly suppressed, suggesting a long lifetime.

We note that there is no evidence for the production of neutral heavy leptons with lifetime less than 10^{-14} seconds in neutrino interactions.[10] The possible decays of an L^{o} of lifetime less than 10^{-10} seconds have not been seen in $e^{+}e^{-}$ annihilation.[11] There is also no evidence for the production of an L^{o} with lifetime greater than 10^{-8} seconds in proton-nucleon collisions.[12] Since an L^{o} may be in a different family than the e or μ, the lack of the decay $K^{+} \rightarrow L^{o} + \mu^{+}(e^{+})$ cannot be used to limit the mass of an L^{o} to above 0.5 GeV/c^2. The anomalous lepton events (τ) observed at SPEAR and DESY may suggest a heavy neutrino mass of less than 0.6 GeV/c^2, but the evidence is not conclusive.[5] Hence, there is a broad lifetime as well as a large mass range in which it is important to search for an L^{o}; this experiment is sensitive in this range. The limits this experiment sets on the lifetime and mass of neutral heavy leptons have relevance to current theoretical work.[13] For relativistic heavy neutral leptons, these lifetimes correspond to distances ranging from centimeters to hundreds of meters in the laboratory. A possible source of heavy neutral leptons would be the creation of L^+L^- pairs in proton-proton collisions, followed by the rapid decay $L^\pm \to L^o + X^\pm$, where X = hadron system or (ℓ, ν_ℓ) with ℓ = lepton. Evidence for an L^o would be the occurrence of the two-body decays $L^o \to \mu^\pm(e^\mp) + \pi^\mp$ in a long decay region downstream of a beamdump.

Our search was conducted in the M2 neutral hyperon beam line at the Fermilab using a multi-wire proportional spectrometer.[14] (See Fig. 1) 400 GeV/c protons were incident upon a 4.9 meter long sweeping magnet which was used as a hadron absorber: the collimated channel of the magnet was plugged with stainless steel rods. A 1.3 meter thick wall of concrete followed the magnet. Behind the concrete, two walls of scintillation counters in coincidence were erected to veto charged particles, mostly muons, which the magnet did not succeed in absorbing or deflecting with its field of 21 kG. Consequently, the experiment was not sensitive to any neutral heavy lepton which may have been produced accompanied by a muon of momentum $\gtrsim$ 10 GeV/c. After the counters, there was a vacuum decay volume of length 9.2 meters and radius 18 centimeters, followed by a multi-wire proportional chamber (MWPC), a scintillation counter TC, two more MWPC's, a superconducting analyzing magnet, and then three more MWPC's. The trigger used was the coincidence of a 30.5 x 30.5 cm^2 scintillation counter with the third MWPC, of height 25.6 cm and width 51.2 cm. The veto array was 95% efficient. Single muons provided most of the triggers. The rate of triggers per beam spill was such that the computer gated off the trigger electronics 72% of the time in order to read out the MWPC data. These single-track events were filtered out in the subsequent computer analysis. The average mass resolution provided by the spectrometer was 10 MeV for Λ^o and 26 MeV for K^o_s.

In an analysis of charge-balanced two-track events where both particles passed through the analyzing magnet, about 1600 events were found to occur with vertices lying within the decay volume corresponding to an integrated luminosity of 2.8 x 10^{13} protons incident upon the plugged sweeping magnet. Most of these events, primarily Λ^o and K^o_s, were found to extrapolate back to an incompletely-plugged channel in the sweeping magnet. After rejecting these events with a fiducial cut, there remained a much smaller background of 20 K^o_s and Λ^o events. Their origins correlated strongly with other possible spaces between pieces of metal extending the length of the magnet. Also remaining was a background of 5 events broadly localized about the incompletely-plugged channel, of mass $\sim$0.3 GeV/c^2 assuming both particles are π's, and of low momentum. These events are consistent with K^o_L's originating in the hole.

The total momentum vector of the two-body decay of an L^o must extrapolate back to a localized region about the beam axis near the front face of the magnetized beam-dump. The beam's diameter was measured to be less than 1 cm. The resolution with which Λ^o and K^o_s tracks were traced to cracks at the magnet back face was .4 cm. The five events were excluded because their extrapolated positions were greater than 5 cm from the beam axis.

A Monte Carlo calculation of the acceptance of the spectrometer for the isotropic decay $L^o \rightarrow \mu^\pm + \pi^\mp$ has been performed for various L^o masses as a function of their lifetime (see Fig. 2). The decay volume as well as the apertures of the first three MWPC's and the analyzing magnet were taken into account. The spectrometer limits the sensitivity to neutral heavy leptons produced with $\theta_{lab} \lesssim 10$ mr with respect to the beam-line axis. We present the case where an L^o is produced with no component of momentum transverse to the proton beam and with Feynman variable $x = p_L^{cm}/p_{MAX} = + 0.2$. The acceptance for heavy neutral leptons of mass 0.5 GeV/c^2 is constant to within 30% at 10^{-2} for $+0.2 \leq x \leq +1.0$ at zero transverse momentum and for $+0.5 \leq x \leq +1.0$ at a transverse momentum of 1 GeV/c. The acceptance for heavier masses rises with increasing x of course, but falls with increasing transverse momentum. At x = 0.2, the acceptance for 0.3 GeV/c^2 is 60% that for 0.5 GeV/c^2. The acceptance for $L^o \rightarrow e^\pm + \pi^\mp$ has also been calculated and is 95% that for $L^o \rightarrow \mu^\pm + \pi^\mp$.

In arriving at an upper limit to the cross-section, we take into account the percentage of time the veto was in effect (1%), the percentage of time the computer gated off the electronics (72%), the 96% overall efficiency of the MWPC's and the 95% efficiency of the trigger, as well as the percentages of data lost to cuts in the computer analysis, namely about 5% to showers and 2% to the fiducial cut on the incompletely-plugged channel in the sweeping magnet. For masses less than 1.0 GeV/c^2, we calculate a minimal acceptance of 5×10^{-4}. We assume a strong interaction cross-section of 40 mb and consider the production of an L^o only in the primary proton-nucleon interaction, not in the accompanying shower. The upper limit on the cross-section for the production of L^o's with $x \gtrsim 0.2$ and $\theta_{lab} \lesssim 10$ mr and their subsequent decay with branching ratio B into two charged particles is $\sigma B \leq 2.8 \times 10^{-35}$ cm^2/nucleon at the 90% confidence level for the mass region less than 1.0 GeV/c^2 and the lifetime range between 10^{-10} and 10^{-8} seconds. In addition, we note that our limits apply to the production of neutral heavy leptons unaccompanied by muons of momentum $\gtrsim$ 10 GeV/c, which would have vetoed the event.

We wish to thank the neutral hyperon groups of Rutgers University and the Universities of Michigan and Wisconsin for the use of their equipment and for the assistance they gave us in the operation of their spectrometer and in the analysis of the data. The staff of the Meson Laboratory at the Fermilab, in particular H. Haggerty, provided enthusiastic support for this experiment.

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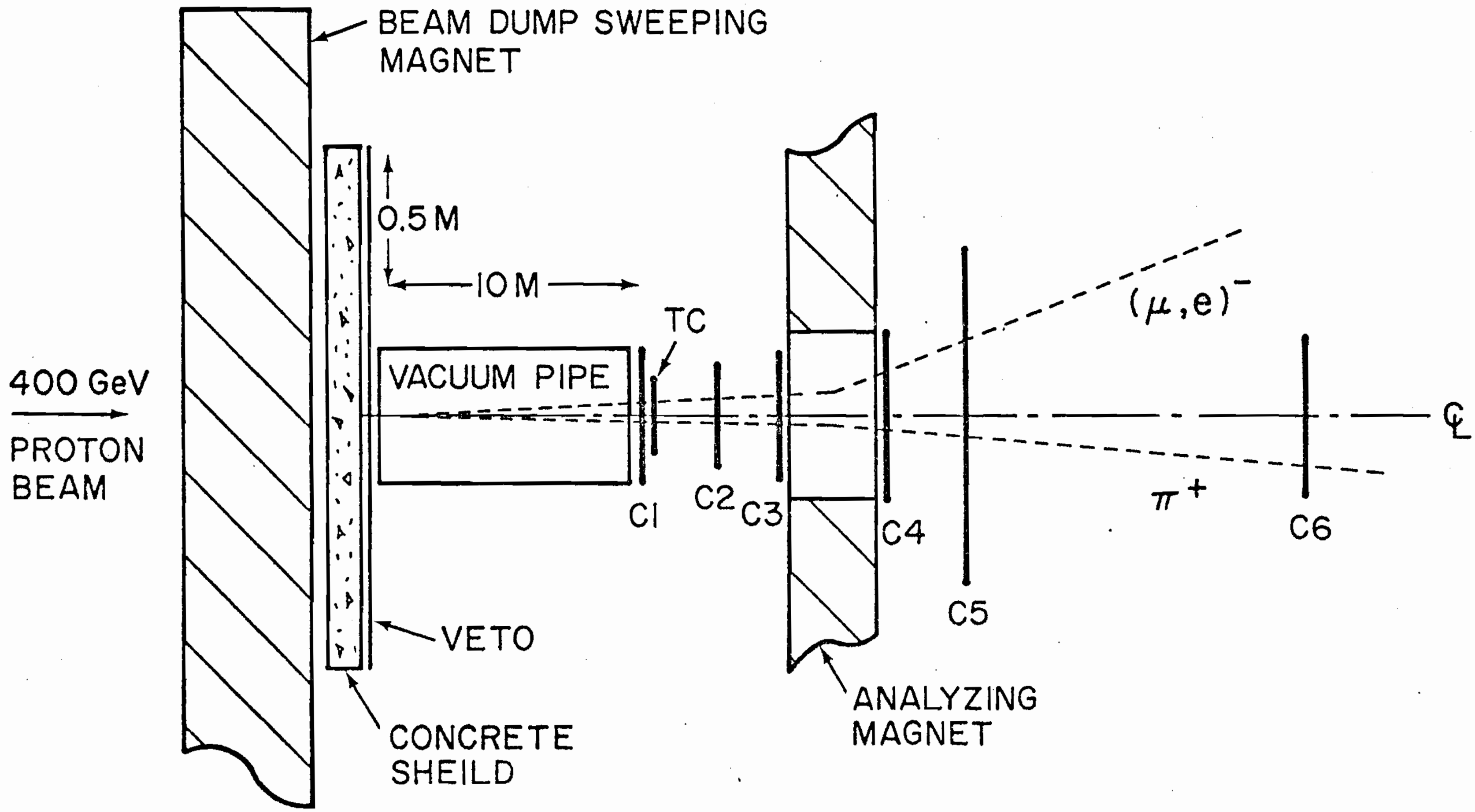
FIGURE CAPTIONS

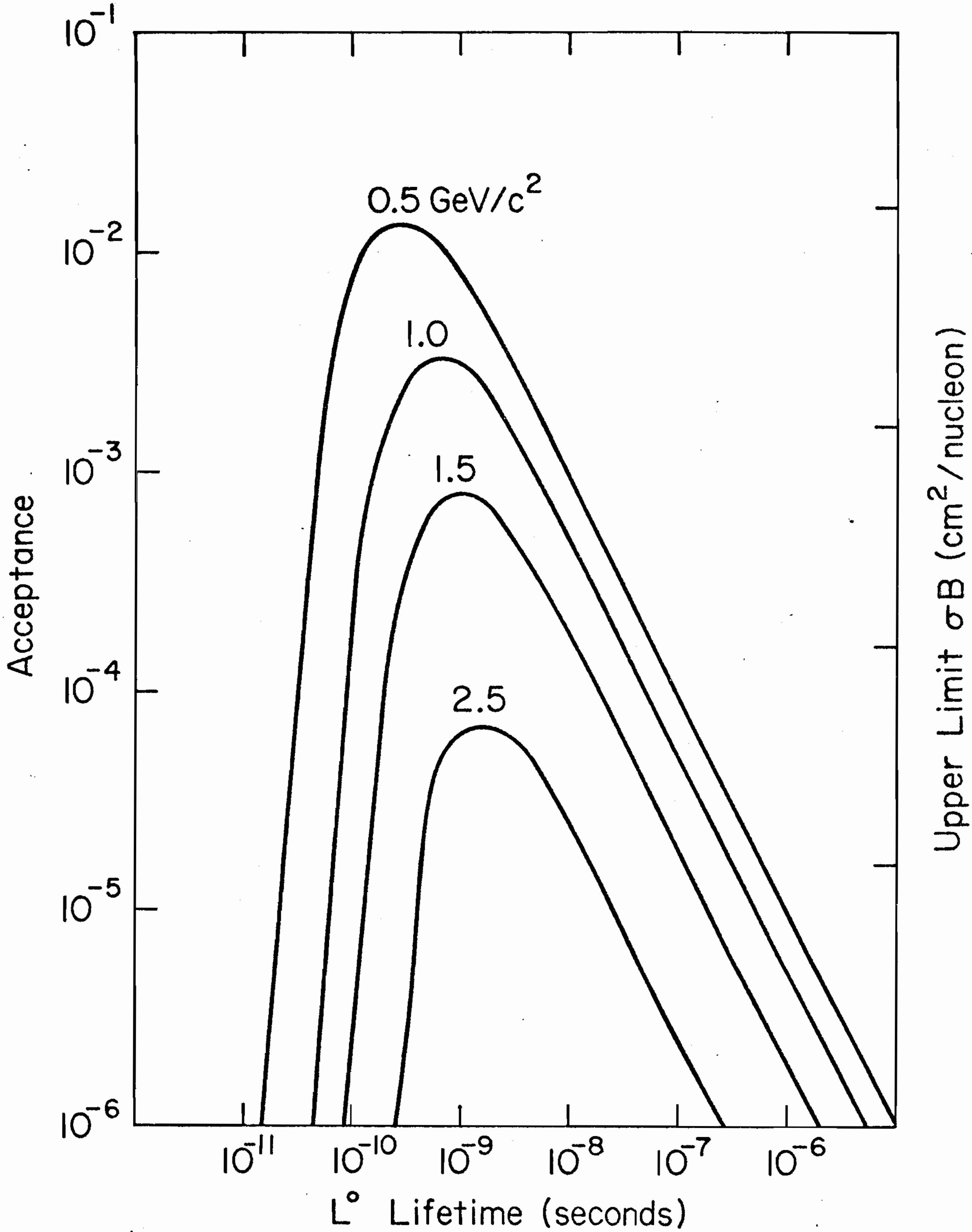
Figure 1. Plan view of experimental apparatus. C1 through C6 are MWPC's and TC is a scintillation counter used in the trigger. The veto consists of two planes of scintillation counters in coincidence. A possible L^{o} decay is indicated.

Figure 2. Acceptance of the spectrometer for the decay $L^{o} \rightarrow \mu \rightarrow \pi$ as a function of the mass and lifetime of a neutral heavy lepton. The L^{o} is assumed to have been created with $x = +0.2$ and no transverse momentum. The right-hand scale gives our measurement of the upper limit at the 90% confidence level on the cross-section for the production of L^{o}'s with $x \gtrsim 0.2$ and $\theta_{lab} \lesssim 10$ mr and their subsequent decay with branching ratio B into 2 charged particles.



BEAM DUMP SWEEPING MAGNET
400 GeV
PROTON BEAM
0.5 M
10 M
VACUUM PIPE
TC
C1
C2
C3
C4
C5
C6
(μ, e)⁻
π⁺
VETO
CONCRETE SHEILD
ANALYZING MAGNET

FIGURE 1



0.5 GeV/c²
1.0
1.5
2.5
Acceptance
Upper Limit σB (cm²/nucleon)
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻¹¹
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
L° Lifetime (seconds)

FIGURE 2