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NEW DATA AND A REVIEW: SEARCHES FOR NEUTRAL HEAVY LEPTONS

G. R. Kalbfleisch

Fermilab*, Batavia, Illinois 60510 and University of Oklahoma, Norman, Oklahoma 73019, USA

Abstract

New data from timing and from mass plots combine with earlier results to narrow the possibilities for the existence of neutral heavy leptons.

1. Introduction

The fundamental fermions appear to be grouped into doublets with respect to the weak interaction in both the quark and the lepton sectors, where the only neutral leptons are massless. It is experimentally imperative to look for other states that might not fit this scheme in order to support (or not) this situation. Various searches for neutral leptons are briefly summarized here. Searches for charged heavy leptons have been given elsewhere.[1)]

2. A Short Review of Published Data

The possibilities for neutral leptons other than the currently observed or postulated neutrinos (ν_e, ν_μ, ν_τ, and their antiparticles) consistent with astrophysical and other data were reviewed by Schramm at Neutrino 78.[2)] Additional (nearly) stable (lifetime τ much greater than the age of the universe) low mass neutral leptons (<10 keV) might exist. Two or three more massless neutrinos would be consistent with the helium abundance in the universe. Heavy neutral leptons of any lifetime and with masses above 100 MeV to 10 TeV (depending on lifetime) could also exist. For masses in the range of 2 to 20 GeV, the astrophysically allowed lifetime regions are $\tau<10^{11}$ seconds, and $\tau>10^{27}$ seconds.

No experimental evidence for other (massless) neutrinos exists. For example, kaonic neutrinos do not exhibit any measured deviations from their pionic counterparts.[3),4)]

For lifetimes of the order of 10^{-8} seconds, the experiment of Benvenuti et al,[5)] excludes neutral heavy leptons below a mass of several GeV. That Fermilab experiment found no excess events within an emptied calorimeter module in the Harvard-Pittsburgh-Wisconsin-Fermilab neutrino detector.

Additionally, dimuon neutrino events[6)] exclude charged or neutral heavy leptons with a short lifetime ($\tau<10^{-9}$ seconds) or masses less than several GeV and for standard leptonic

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branching ratios (otherwise the observed dimuon yields would have to be several times larger). However, in spite of this, some evidence for a neutral heavy lepton L° (1.85 GeV) decaying to $\mu^-\pi^+$ has been reported by Bosetti et al.[7] If confirmed, this state would require an anomalously small coupling ($<<G^2_F$)

3. New Data

3.1 From Timing

Timing of 10^4 neutrino and antineutrino events with respect to the Fermilab accelerator's rf signal[4] has been carried out in an experiment using the dichromatic beam and the CalTech-Fermilab neutrino detector. All charged current events whose muons are observed to traverse the timing counters are essentially in time with the rf signal. The two timing counters yield a scattergram of one versus the other each relative to the rf. A diagonal strip of this scatterplot is shown in Figure 1a. The neutrino and antineutrino data represent about 8×10^{17} 400 GeV protons on target. A subsample of muons arising from the upstream decay region were also allowed to trigger the detector. The corresponding piece of the scatterplot for these 10^4 muons of opposite sign to those in the neutrino (antineutrino) events respectively is shown in Figure 1b. The shapes of the peaks in the projections of these scattergrams are nicely Gaussian out to four standard deviations. Beyond that, errors in one of the times (say from a noise pulse preceding the muon, or a noise pulse following a muon not registered) account for the balance of the events for both the neutrino events in Figure 1a and the decay muons in Figure 1b. Thus, an upper limit on the number of events that are out of time with the rf signal, in a $\Delta\gamma$ band from 10 to 20, is given by the difference in the numbers of events in the "octagonal" regions of Figure 1. This upper limit is $N\lesssim7$ (ninety percent confidence level).

This null observation can be interpreted as an upper limit on L°, $\overline{L^\circ}$ production by 400 GeV protons on nuclei (aluminum in the target and iron or aluminum in the subsequent beam dumps on the dichromatic train). These L° and $\overline{L^\circ}$ can either interact

$$L^\circ(\overline{L^\circ}) + N \rightarrow \mu^\pm X \qquad (1)$$

or decay

$$L^\circ(\overline{L^\circ}) \rightarrow \mu^\pm X \qquad (2)$$

in the neutrino detector. Using particular models for reaction (1) Shrock[8] has calculated the yield of "charged current" like events arising from such neutral heavy leptons. Two examples, including the acceptance of the detector for the muons to traverse the timing counters, are shown in Figure 2. The value of σ/E for L° masses of 1.8 and 4.0 GeV as a function of the L° energy are given. The crosshatched region corresponds to the $\Delta\gamma$ band of the "octagonal" region of Figure 1. L° leptons give similar curves, differently normal-

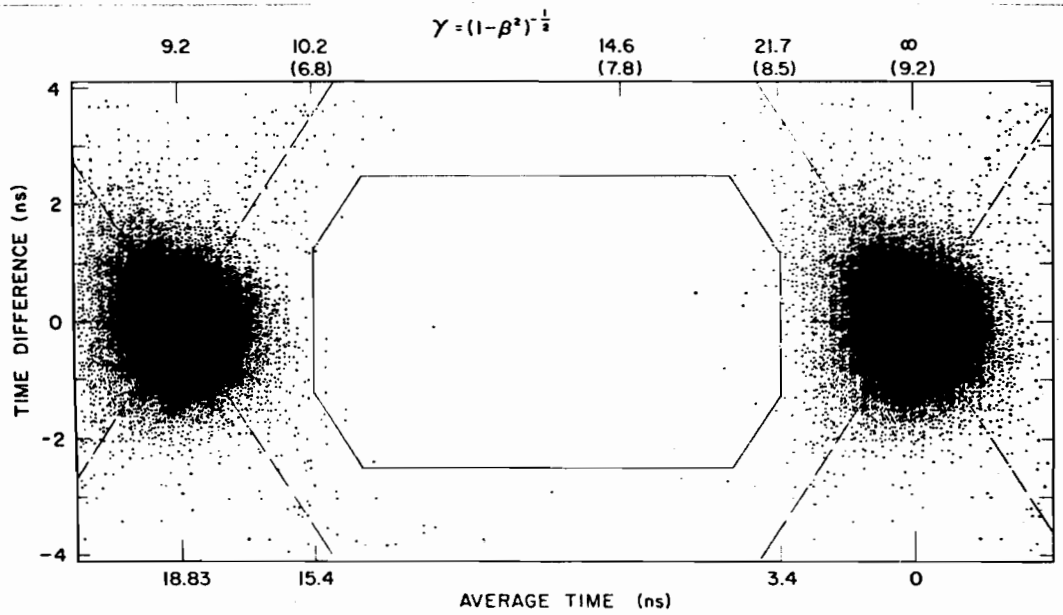

Figure 1a. Sum and difference of timing of two counters relative to the accelerator rf signal for 10^4 neutrino and anti-neutrino events whose muons traverse the toroidal magnet and timing counters. The concentrations of events occur at the time of the proton bunches and are separated by 18.83 ns (53.1 MHz frequency). The "octagonal" region encloses those events consistent with slow particles with the relativistic γ factor as shown at the top.

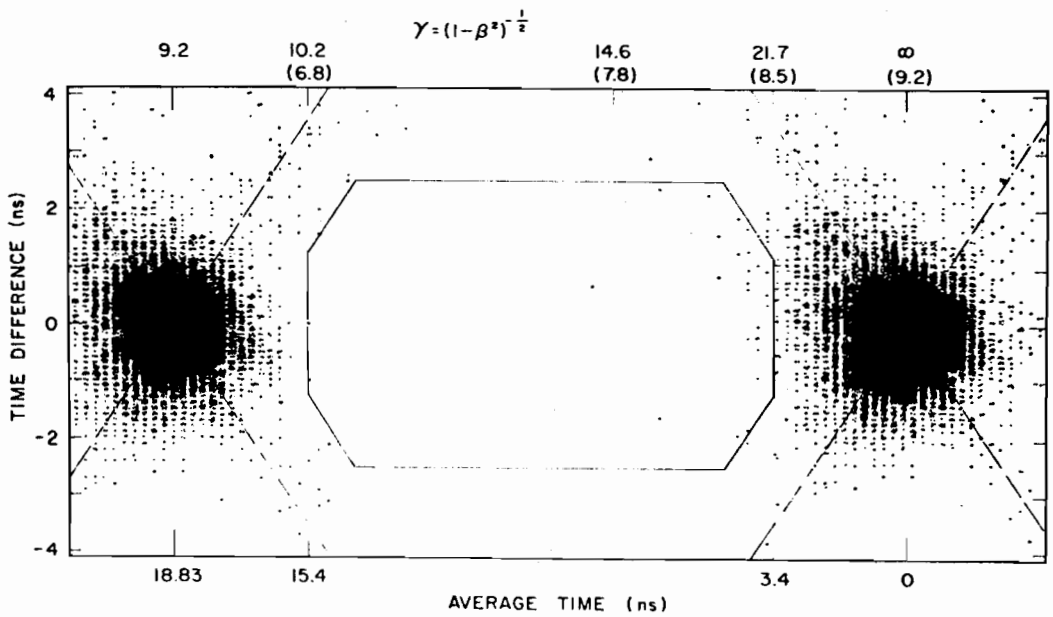

Figure 1b. Same distribution as 1a, for scaled down sample of penetrating muons from the hadronic decay space 700 meters upstream of the neutrino detector.

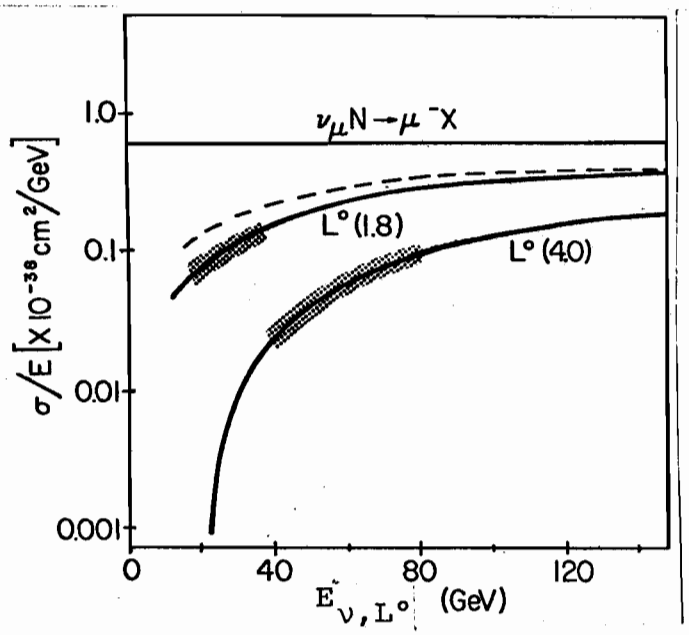

Figure 2. σ/E for neutrino interactions (horizontal line) and including the acceptance factor for the muon to traverse the timing counters (dashed curve) and for reaction (1) according to Shrock's model including $\mu^\pm$ acceptance for L° masses of 1.8 and 4.0 GeV.

ized. The resultant upper limit for the $L^\circ(\overline{L^\circ})$ flux and the differential cross section $d^2\sigma/d\Omega/d\gamma$ (for 400 GeV $pN \to L^\circ\overline{L^\circ}X$) are shown in Figure 3 as the asymptotic value at very long lifetimes.

Unstable $L^\circ(\overline{L^\circ})$, decaying via reaction (2) can also be observed in the detector. The average acceptance should be about ninety percent. The branching ratio (B) might be ten percent. The number N of $L^\circ+\overline{L^\circ}$ (not corrected for B) is related to the observed laboratory time t in nanoseconds ($=\gamma\tau$, where τ is the proper lifetime) by

$$N \lesssim 0.25\ t \exp(3200\ t) \qquad (3)$$

This function cuts off at low and high times, as shown in Figure 3. At times $t \sim 10^3$ seconds, the interaction rate and the decay rate give comparable limits.

The most optimistic level of production of 1.8 GeV $L^\circ(\overline{L^\circ})$ is expected to be at or below the asymptotic upper limit shown in Figure 3. This level corresponds to $(L^\circ,\overline{L^\circ})/\pi \sim 10^{-5}$, as compared to a known μ (or e)$/\pi \sim 10^{-4}$ and the level expected for a mass of 4.0 GeV is some three orders of magnitude lower. Thus the upper limit on stable $L^\circ(\overline{L^\circ})$ is too high to rule out the existence of such states from 1.5-5 GeV mass. However, for unstable L°, the upper limit for masses 1.5-5 GeV apparently excludes such states for lifetimes of $10^{-8} < \tau < 10^{-4}$ seconds for B = 0.1.

3.2 From Mass Plots

From a Fermilab 15-foot bubble chamber experiment, mass plots[9] of muons plus pions from 1200 neutrino and 1200 antineutrino charged current events have been examined for structure due to possible short lived neutral heavy leptons decaying via reaction (2). No structure has been observed over a

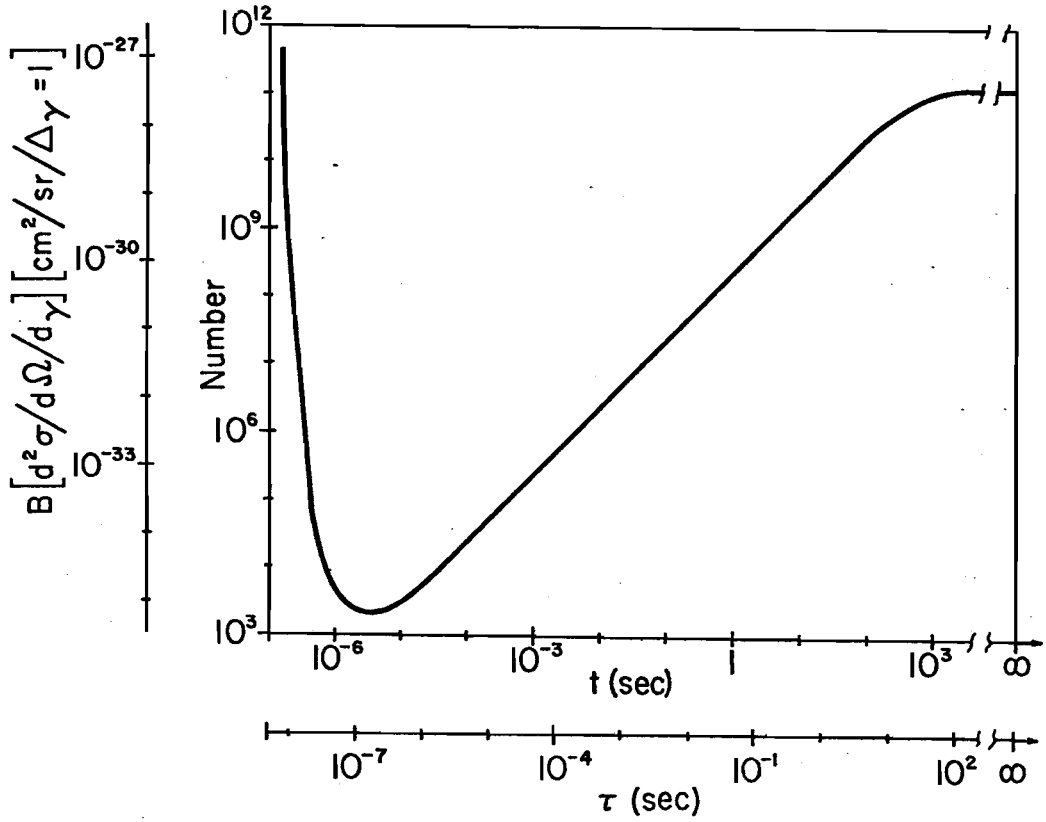

Figure 3. Upper limits on $L^\circ+\overline{L^\circ}$ flux versus time for an exposure of the CalTech-Fermilab detector to 8×10^{17} protons on target: number versus laboratory time and cross section versus proper lifetime. The branching ratio B is taken as one for the horizontal portion of the curve representing interactions in the detector.

mass range from 0 to 12 (or 20) GeV. Calculations of the expected yields of muonic $L^\circ(\overline{L^\circ})$ production from neutrino interactions

$$\nu_\mu(\nu_\mu)+N\rightarrow L^\circ(\overline{L^\circ})+X \tag{4}$$

relative to normal single muon charged current events

$$\nu_\mu(\nu^-_\mu)+N\rightarrow\mu^-(\mu^+)+X \tag{5}$$

show that the ratio R is approximately constant for each assumed mass value if the neutrino energy is above three times the threshold value. Using the new statistical procedure of L. Fluri, the upper limit to the ratio R at ninety percent confidence level of $(L^\circ\rightarrow\mu^\pm+n\pi)$ relative to reaction (5) as a function of mass, using an energy cut of the larger of 20 GeV or three times the threshold value, have been calculated. Two examples for R versus mass are shown in Figures 4 and 5. The combined 2400 event sample yields limits of $(\mu^\pm\pi^\mp)$ states of less than one percent up to a mass of 12 GeV. The 1200 antineutrino events give an upper limit for $(\mu^+(5\pi)^-)$ states which

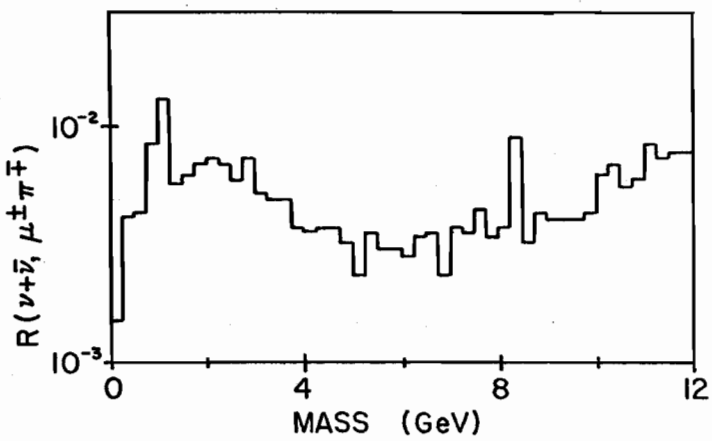

Figure 4. Ninety percent confidence upper limits for the ratio R of possible $L^{o}(\overline{L^{o}}) \rightarrow \mu^{\pm}\pi^{\pm}$ to numbers of events of reaction (5) (see text) versus $L^{o}(\overline{L^{o}})$ mass.

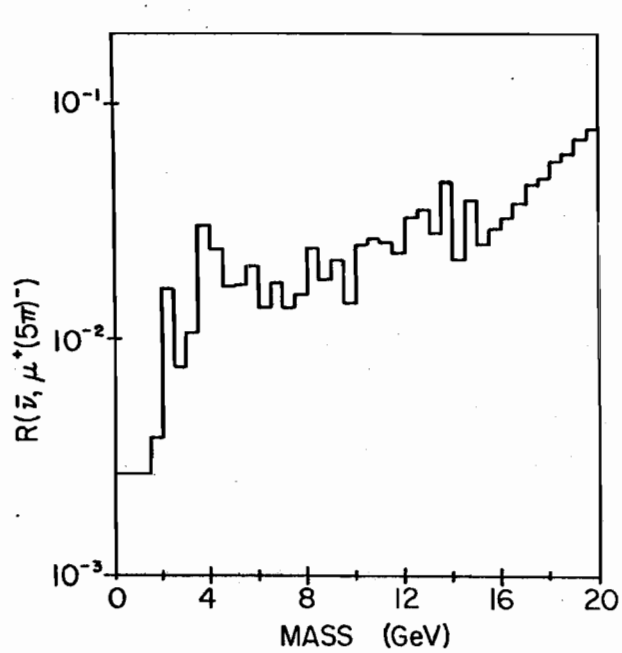

Figure 5. Ratio R (see Figure 4) for $\overline{L^{o}} \rightarrow \mu^{+}(5\pi)^{-}$ relative to antineutrino interactions as function of $\overline{L^{o}}$ mass.

rise from approximately one percent at low mass to about ten percent at 20 GeV. Clearly much larger statistics taken with a hardened neutrino beam would be very desirable to significantly improve these ratios.

Combining the upper limits from $\mu^{\mp}\pi^{\pm}$, $\mu^{\mp}(3\pi)^{\pm}$ and $\mu^{\mp}(5\pi)^{\pm}$, we obtain an estimate of the upper limit to $L^{o}(\overline{L^{o}})$ production for lifetimes less than 10^{-11} seconds (flight paths less than one centimeter in the bubble chamber). The pi-zeros have not been measured in these events. Various models give an estimate for a correction factor for the unanalyzed states. A value of two is a reasonable factor. Table I estimates the upper limit in three mass ranges 0-3, 3-10 and 10-16 GeV. One theoretical estimate for a coupling strength of 0.4 G^{2}_{F} is also given in Table I. The estimated upper limits are compared to the theoretical curve in Figure 6. Neutral heavy leptons with a mass below about 4-5 GeV appear to be ruled out regardless of branching ratios unless the coupling is unexpectedly low.

TYPING AREA STARTS HERE

TABLE I

a) Expt. (E-172)	[1200 νcc + 1200 ν̄cc] M<3	3<M<10	10<M<16
μπ	<.02	<.01	<.01
μ3π	<.02	<.03	<.03
μ5π	<.004	<.04	<.05
Sum X2	<.09	<.16	<.18
b) Theory	($E_\nu > 3\times E_{thres.}(M)$)		
M	3	5	7 9 GeV
$0.4G^2_F$	0.25	0.12	0.08 0.05

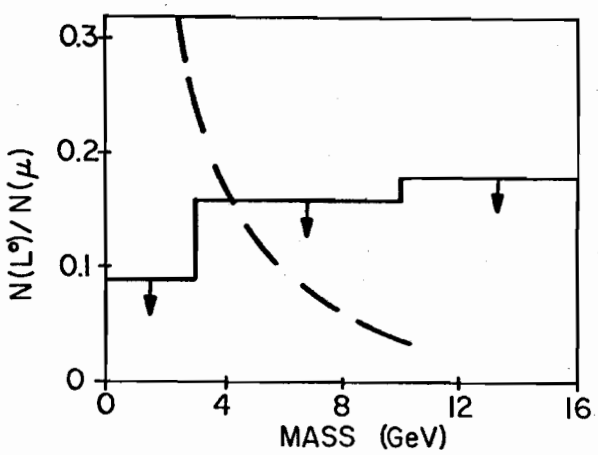

Figure 6. Upper limits on ratio of number of $L^\circ+\overline{L^\circ}$ relative to neutrino plus antineutrino events versus mass, from data in Table I. Data, solid lines; theory, dashed curve (see text).

4. Discussion

No evidence is found in these new data for neutral heavy leptons for lifetimes $\tau<10^{-11}$ seconds or $\tau>10^{-8}$ seconds. For the mass range 1.5-5 GeV and $\tau<10^{-11}$ second or $10^{-8}<\tau<10^{-4}$ second, the data appear to rule out the existence of neutral heavy leptons unless the coupling strenghts are anomalously low. For the lifetime range $10^{-11}<\tau<10^{-8}$ seconds, the bubble chamber data, if examined for decay vertices in the range one centimeter to two meters, could supply additional upper limits. For $\tau>10^{-4}$ seconds, more sensitivity is needed. Provision for timing of the hadron calorimetry in neutrino detectors in addition to the muons and extension of the exposure to say 10^{20} protons on target would yield significant limits covering the whole lifetime spectrum for masses up to many GeV.

The $\mu^{\pm}\pi^{\mp}$ spectra of Figure 4 and upper limits in Table I do not support the observation by Bosetti et al, of a possible $\mu^{-}\pi^{+}$ state. Benvenuti's data rules out neutral heavy leptons with a lifetime about 10^{-8} seconds. Thus neutral heavy leptons have not been observed to date, although the sensitivity of the searches are not sufficiently sensitive in certain mass and lifetime regions for normal reasonable coupling strengths.

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