Search for Neutral Heavy Leptons from ν-N Scattering

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Results are presented on a search for neutral heavy leptons that couple to muon neutrinos in high-energy neutrino-nucleon interactions (E_ν=30–230 GeV). No evidence for such particles is observed. We obtain upper limits on the coupling of neutral heavy leptons to ν_μ below Fermi strength in the mass range 0.25–14 GeV/c^2.

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Neutral heavy leptons (NHL's) have been conjectured in many theoretical models. These models include grand unified theories (GUT's) where NHL's correspond to massive right-handed neutrinos occurring as singlets under the standard SU(2) gauge group,[1–3] postulates of recurrences of the existing lepton flavors, e.g., $(\nu_\mu,\mu^-)\leftrightarrow(M^0,M^-)$,[4] and extensions of the standard model proposing the NHL as a fourth-generation massive neutrino. Past searches for NHL's have obtained limits by the use of π and K decay,[5–7] beam dump experiments,[8,9] and e^+e^- experiments.[10,11] Different techniques are sensitive to different models of NHL's, mass ranges, and coupling strengths. We present a unique search for an NHL, where the NHL is produced by the ν_μ-nucleon neutral-current interaction, in a high-energy neutrino scattering experiment. We have parametrized the results in terms of a GUT NHL, predicted to behave as singlet under the weak-isospin group of the standard model,[12] although the search could apply to any NHL having some finite coupling to ν_μ. The search is sensitive to lepton masses up to 14 GeV/c^2 for muon couplings below Fermi strength (G_F).

Neutrino data were accumulated in the Fermilab dichromatic neutrino beam[13,14] with the Caltech-Columbia-Fermilab-Rochester-Rockefeller detector over two running periods[14–16] in which a total of 5.4×10^{18} 400-GeV protons were incident on a BeO target. The produced secondary pions and kaons were selected by momentum ($\delta P/P\approx 10\%$) and sign; these traversed a 352-m evacuated decay region to provide ν_μ at the detector located 1040 m farther downstream. Usable neutrino energies (E_ν) spanned 30–230 GeV. The detector consisted of a 640-ton iron target calorimeter with liquid scintillation counters and muon-tracking spark chambers, followed by a 340-ton toroidal muon spectrometer also instrumented with spark chambers. The rms fractional resolution[15] of the measured hadron energy was $(0.89\ \text{GeV}^{1/2})/\sqrt{E_h}$ and that of the muon momentum 0.11. The present study was conducted with a sample of 164000 charge-current (CC) and 50000 neutral-current (NC) ν_μ-N interactions, with a measured fractional antineutrino contamination of 10^{-3}.

The production of a muon-type NHL $\mathcal{N}_\mu$ in ν_μ-N scattering via the NC interaction can be parametrized in terms of the neutrino NC cross section.[2] If U^2 represents the heavy-lepton-to-ν_μ coupling relative to G_F, the $\mathcal{N}_\mu$ with mass M will be produced with the cross section given by[17]

$$\frac{\sigma(\nu_\mu+N\rightarrow\mathcal{N}_\mu+X)}{\sigma(\nu_\mu+N\rightarrow\nu_\mu+X)}=U^2\left(1-\frac{M^2}{2m_N xE_\nu}\right)^2.$$

The factor in parentheses on the right-hand side expresses the threshold dependence, where x is the fractional momentum carried by the struck quark and m_N is the mass of the nucleon. Since the $\mathcal{N}_\mu$ has a weak charge, it can decay in general by either the CC or NC mode to leptons and hadrons. We searched for two $\mathcal{N}_\mu$

signatures: (1) dimuon events from $\mathcal{N}_\mu \to \mu^- + \mu^+ + \nu_\mu$ with a predicted branching ratio (PBR)[2,11] of 10% and kinematics distinct from events due to conventional hadronic sources such as dimuons originating from charm or π/K decays; and (2) $\mathcal{N}_\mu$ decays to hadrons or muons through the modes $\mathcal{N}_\mu \to \mu^- + X$ (PBR=55%), $\mathcal{N}_\mu \to \nu_\mu + X$ (PBR=21%), or $\mathcal{N}_\mu \to \mu^- + \mu^+ + \nu_\mu$, with lifetimes long enough so that a secondary vertex would appear downstream of the primary production vertex.

For the first study, the candidate dimuon events were visually scanned and, if necessary, interactively reconstructed by physicists.[18] The measured efficiency for a dimuon to reach this sample is greater than 99%. These dimuons were required to have a vertex with transverse coordinates within a $2.7 \times 2.7\text{-m}^2$ square, a longitudinal coordinate at least 3.4 m (1.7 m of iron) upstream of the front face of the spectrometer, and the muon momenta P_{μ^+} and P_{μ^-} each greater than 4.5 GeV. 553 dimuon events satisfied these fiducial and momentum cuts (these cuts were slightly different from those discussed in Ref. 18). These dimuon events were then subjected to cuts that eliminated conventional sources of $D/K/\pi$-meson decay, while keeping the $\mathcal{N}_\mu$ efficiency high. Conventional sources require highly asymmetric production of μ^- (which originates at the lepton vertex) and μ^+ (which originates at the hadron vertex from the subsequent $D/K/\pi$-meson decay). In contrast, the μ^- and μ^+ from $\mathcal{N}_\mu$ decay occur symmetrically for essentially any model of decay. To be specific, three specialized cuts were employed:

(1) The azimuthal angle ϕ^{-+} between μ^+ and μ^- in a plane perpendicular to the beam direction must be less than 120°. The ϕ^{-+} distribution for the muon pair, where μ^+ originates at the hadron vertex, is expected to peak at 180°, whereas the corresponding distribution should be flatter if the dimuon emerges from $\mathcal{N}_\mu$ decay. Figure 1(a) shows the ϕ^{-+} distributions for the data (solid line) and for a Monte Carlo simulation of a 5-GeV/c^2 $\mathcal{N}_\mu$ (dashed line). 171 data events passed this cut.

(2) The transverse momentum P_+^T of μ^+ with respect to the beam direction must be greater than 1.2 GeV. The extra μ^+, a decay product of a $D/\pi/K$ meson, has a smaller P_+^T than the one originating from a heavy (mass > 2 GeV) $\mathcal{N}_\mu$. Only one event among the 171 survived this cut. Figure 1(b) illustrates the P_+^T distributions after the azimuthal-angle cut was imposed.

(3) The ratio of the two muon momenta, P_{μ^+}/P_{μ^-}, must be greater than 0.1.[19] The asymmetric muon momenta, characteristic of the conventional dimuon events, provided an additional handle in extracting the $\mathcal{N}_\mu$ signal. Whereas the imposition of this cut did not effect the simulated $\mathcal{N}_\mu$ events, it eliminated the remaining event in the data.

Table I shows that a large fraction of simulated dimuons from $\mathcal{N}_\mu$ decay pass these cuts and none of the data dimuons remains. The numbers of $\mathcal{N}_\mu$ shown in Table I are calculated for a coupling only 1% of G_F. The fiducial cuts reduce the raw data sample and the calculated NHL samples about the same (about 50%). The specialized kinematic cuts remove all of the dimuon data, as expected for dimuons from conventional sources. The efficiency of these specialized cuts for NHL is independent of U^2 and, as seen in Table I, is largely independent of M (0.37–0.48 for $2 < M < 10$ GeV). The null result of the experiment combined with Monte Carlo efficiency calculations for different masses of $\mathcal{N}_\mu$ then yields the 90%-confidence-level limits shown in Fig. 2, curve *a*.

For the second study, each observed ν_μ-induced event (214×10^3 events) was examined for a secondary vertex starting 1 m (5.4 interaction lengths) downstream of the end of the shower from the primary vertex.[20] The secondary vertex was required to have two consecutive counters with pulse heights corresponding to greater than ten minimum ionizing particles (2.2 GeV).[21] Back-

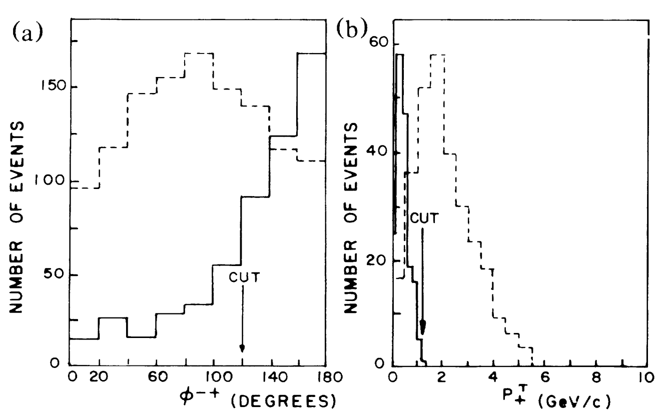

FIG. 1. (a) Distribution of the azimuthal angle between the two muons, ϕ^{-+}. The solid line represents data and the dashed line represents dimuons from a 5-GeV/c^2 $\mathcal{N}_\mu$ with $U^2=1$. (b) Distribution of P_+^T, requiring that $\phi^{-+} < 120°$, for data (solid line) and $\mathcal{N}_\mu$ dimuons (dashed line).

TABLE I. Effect of fiducial and kinematical cuts on dimuon events from the data and the Monte Carlo of an $\mathcal{N}_\mu$ with specified mass (in GeV/c^2) and coupling.

		2μ NHL Monte Carlo		
	2μ data	$M=2$, $U^2=10^{-2}$	$M=5$, $U^2=10^{-2}$	$M=10$, $U^2=10^{-2}$
Raw number	1053	30	8.68	1.05
Fiducial cut	553	15	4.39	0.52
Specialized kinematic cuts				
$\phi^{-+} < 120°$	171	13.9	3.03	0.27
$P_+^T > 1.2$	1	5.5	2.30	0.25
$P_{\mu^+}/P_{\mu^-} > 0.1$	0	5.5	2.30	0.25

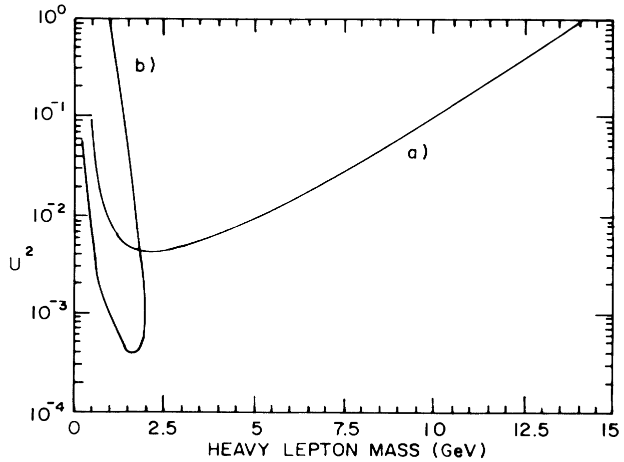

FIG. 2. Upper limits for NHL coupling to ν_μ, U^2 vs its mass M. The dimuon search yields the limit a and the double-vertex search yields the limit b. An uncertainty of 20% in the Monte Carlo simulation for both studies is included in the limits.

ground from standard CC events (where the outgoing μ^- underwent an inelastic electromagnetic scattering) was eliminated by our requiring that the emergent lepton be neutral. This was accomplished by our demanding that the average pulse height in the counters between the end of the shower from the primary vertex and the start of the second vertex must be less than 0.5 times minimum ionizing per counter. No event in the data sample passed these cuts. Background from two in-time neutrino interactions was calculated to be less than 0.3 event. To obtain a limit on $\mathcal{N}_\mu$ production, a Monte Carlo calculation was performed incorporating the $\mathcal{N}_\mu$ lifetime,[2] the geometrical acceptance for $\mathcal{N}_\mu$ events, and loss of events where the second vertex might get obscured by the primary hadron shower. The inefficiency due to a loss of the secondary vertex in the primary hadron shower was estimated with data accumulated during running in a charged hadron beam of well-defined momentum directed at the neutrino apparatus.[22] These calculations together with the absence of double-vertex events in the data lead to the 90%-confidence-level limits shown in Fig. 2, curve b. The curve is double valued because of two competing effects for the decay of an $\mathcal{N}_\mu$: For a given mass, if the coupling of the $\mathcal{N}_\mu$ were larger than a certain value, the $\mathcal{N}_\mu$ would decay almost immediately after production with the secondary vertex obscured by the primary hadron shower; alternatively, if the coupling were smaller than a certain value, the $\mathcal{N}_\mu$ would escape from our detector without decaying. Furthermore, our double-vertex search is insensitive to $\mathcal{N}_\mu$ masses greater than 2 GeV because, with 3×10^{-4} as the lowest attainable value of U^2 (we have 50000 NC events), the heavy lepton ($M>2$ GeV) would decay in too short a time to produce an observable double-vertex signature. It should be noted that curve b is similar to limits imposed in a similar search by Dorenbosch *et al.* (the CHARM Collaboration).[9]

Results presented in this analysis directly apply to an NHL which behaves as a singlet with respect to the weak isospin in the standard model as predicted by some grand unified models.[1-3,12] Our limits as presented in curve a in Fig. 2 are sensitive to an order of magnitude higher $\mathcal{N}_\mu$ masses than those previously published.[5-9] It is true that muon-electron universality tests put limits on couplings of the ν_μ to heavy neutrinos under certain model-dependent assumptions in the context of grand unified theories.[2,12] For example, the ratio[23] $\Gamma(\pi\to e\nu)/\Gamma(\pi\to\mu\nu)$ would restrict U^2 to below 0.011, if one assumed that the coupling of $\mathcal{N}_\mu$ to ν_μ is very different from the coupling of $\mathcal{N}_e$ to ν_e. With this assumption, our result still gives a more stringent limit on U^2 in the mass range 0.5–5.5 GeV/c^2. Finally, these limits constrain several other classes of models for NHL's as well.[24]

In conclusion, we observe no evidence for neutral heavy lepton production by muon neutrinos. Our results exclude the existence of a muon-type NHL in the mass range 0.25–14 GeV/c^2, for muonic coupling below Fermi strength, as shown in Fig. 2.

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[20]This constrains the position of the secondary vertex to be, on the average, thirteen interaction lengths downstream of the primary vertex. Therefore, the probability for a neutral hadron (K^0, neutron star, etc.) to form a secondary vertex is negligible.

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[24](a) An NHL appearing as a fourth-generation neutrino, provided that flavor changing NC processes are permitted. (b) An NHL which is a recurring neutrino (Ref. 4) with quantum numbers similar to ν_μ. (c) An NHL predicted to be a massive predominantly right-handed neutrino (Ref. 2). (The limits presented here are valid for this type of neutrino with only minor modifications.)