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Search for Neutral Heavy Leptons in a High-Energy Neutrino Beam

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A search for neutral heavy leptons (NHLs) has been performed using an instrumented decay channel at the NuTeV (E-815) experiment at Fermilab. The decay channel was composed of helium bags interspersed with drift chambers, and was used in conjunction with the NuTeV neutrino detector to search for NHL decays. The data were examined for NHLs decaying into muonic final states ($\mu\mu\nu$, $\mu e\nu$, $\mu\pi$, and $\mu\rho$); no evidence has been found for NHLs in the 0.25 - 2.0 GeV mass range. This analysis places limits on the mixing of NHLs with standard light neutrinos at a level up to an order of magnitude more restrictive than previous search limits in this mass range.

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Various extensions [1,2] to the Standard Model predict neutral heavy leptons (NHLs) which can mix with the standard light neutrinos. In these extensions, the NHLs are weak isosinglets that do not couple directly to the Z and W bosons, but can decay via mixing with the Standard Model neutrinos. Figure 1 shows one possible set of tree-level diagrams for NHL production and decay. The NuTeV (E815) neutrino experiment at Fermilab has made a sensitive search for these NHLs by combining the capabilities of a high intensity neutrino source with an instrumented decay region.

In these extended models [1], the NHL lifetime depends on the mixing parameter $|U|^2$ and the mass of the NHL. They are expected to decay (e.g. Fig. 1b) into a neutrino and two charged leptons, into a lepton and two quarks, or into three neutrinos.

NHLs may be created in the NuTeV beamline by the decays of secondary mesons produced by the Tevatron proton beam. During the 1996-1997 fixed-target run at Fermilab, NuTeV received 2.54×10^{18} 800 GeV protons on a beryllium oxide production target with the detector configured for this search. A sign-selected quadrupole train focused secondary π and K mesons down a beamline 7.8 mrad from the primary proton beam direction. 1.13×10^{18} protons were received with the magnets set to focus positive mesons, and 1.41×10^{18} protons with negative meson focusing. The mesons could decay into NHLs as shown in Fig. 1a. The production of secondary pions and kaons was simulated using the parameterization in [3]; the Decay Turtle program [4] simulated the propagation of charged particles through the beamline.

NHLs may also be produced by prompt decays of charmed mesons produced by incident protons on the BeO target and proton dumps. These processes were simulated using a Monte Carlo program based on measured production cross sections [5]. The effects of decay phase space, NHL polarization, and helicity suppression [6] were included in the simulation of the production and decays. For NHLs of mass 1.45 GeV from D meson decay, the average momentum was $\sim$100 GeV; for the 0.35 GeV NHLs coming mainly from K decay, the average momentum was $\sim$140 GeV.

This analysis reports the results of a search for NHLs with masses between 0.25 to 2.0 GeV, which decay with a muon in the final state. The primary NHL decay modes of this type are $\mu e \nu, \mu\mu\nu, \mu\pi$, and $\mu\rho$. In the standard mixing model [1,7], the expected ratio of decay rates for $\mu\pi : \mu e\nu : \mu\mu\nu$ is $3.5 : 1.6 : 1.0$. The $\mu\rho$ channel is significant only for NHL masses above 1 GeV, where it is comparable to the $\mu\pi$ mode.

In order to detect NHL decays, an instrumented decay region (the "decay channel") was constructed 1.4 km downstream of the production target. The decay channel (Fig. 2) was designed to identify signatures characteristic of NHLs: a neutral particle decaying to two charged particles within the decay channel. A 4.6 m $\times$ 4.6 m array of plastic scintillators vetoed charged particles entering from upstream. The decay channel was 34 m long, interspersed with 3 m $\times$ 3 m multi-wire argon-ethane drift chambers positioned at 15.4 m, 25.2 m, 35.5 m, 36.8 m, and 38.5 m downstream of the veto array. Tracks were reconstructed from drift chamber hits and grouped to form candidate decay vertices. Typically, a vertex from a NHL of mass 1.15 GeV was reconstructed with a resolution of 0.04 cm in the transverse direction and 28 cm in the longitudinal direction. The region between the drift chambers was filled with helium contained in cylindrical plastic bags 4.6 m in diameter. By displacing the air with helium, the number of background neutrino interactions between the chambers was reduced by a factor of 7.

The Lab E neutrino detector [8], located immediately downstream of the decay channel, provided final state particle identification, energy measurement, and triggering. This detector consisted of a 690-ton iron-scintillator sampling calorimeter followed by a toroidal muon spectrometer. Drift chambers were positioned every 20 cm along the length of the calorimeter, and 2.5 cm-thick liquid scintillator counters were interleaved with 10 cm steel plates along the length of the calorimeter. The trigger selected events with a penetrating muon or at least 6 GeV of hadronic or electromagnetic energy in the calorimeter. Offline, hits in the calorimeter drift chambers were analyzed to determine if they formed a track (consistent with a muon) or a cluster of hits (consistent with an electron or pion shower).

Tracks found in the decay channel were linked to clusters or tracks in the calorimeter. Pulse height information from the scintillation counters was used to determine hadronic or electromagnetic energy deposition; the hadronic energy resolution of the calorimeter was $\frac{\sigma}{E} = 0.024 \oplus \frac{0.87}{\sqrt{E}}$, and the electromagnetic energy resolution was $\frac{\sigma}{E} = 0.040 \oplus \frac{0.52}{\sqrt{E}}$. Muon energies were determined either by the toroid spectrometer (with 11% resolution) or by range (with a resolution of 155 MeV). The energy of muons which exited through the side of the calorimeter was determined from the track's multiple scattering, with a resolution of 25% for energies lower than 85 GeV.

The following processes were the main backgrounds to this search: 1) neutrino interactions within the helium; 2) neutrino interactions in the material upstream of the decay channel, where a neutral kaon survived to the decay channel and decayed in the fiducial volume; and 3) neutrino interactions in the material surrounding the decay channel. Neutrino interaction backgrounds could arise from low multiplicity resonance production or from deep inelastic scattering (DIS). Resonance production was simulated using the calculations of Belusevic and Rein [9]; such events were characterized by a high-energy muon accompanied by a low-energy pion track. The Lund Monte Carlo program was used to simulate

DIS events [10]. While these were generally of high multiplicity, events with few or poorly-reconstructed tracks could contribute to the two-track background. The detector was simulated using the GEANT [11] Monte Carlo, which produced a hit-level simulation of raw data including beam and cosmic ray related noise hits. These were processed using the same analysis routines as those used for the data.

Backgrounds from cosmic rays were estimated using a sample of cosmic ray muons which interacted in the target calorimeter; an upper limit of 10^{-3} background events was determined. We have therefore ignored cosmic rays in the final background estimate.

Event selection criteria maintained high efficiency for the NHL signal while minimizing known backgrounds. Cuts fell into two broad categories: reconstruction and kinematic.

Reconstruction cuts isolated events with a two-track decay vertex within the decay channel fiducial volume and no charged particle identified in the upstream veto system. The two tracks were required to be well-reconstructed, have an accompanying energy measurement, and form a common vertex. Large angle tracks arising from cosmic rays were removed by requiring tracks to form an angle of less than 0.1 radians with the beam direction. Exactly two tracks were required, both projecting to the calorimeter, with at least one of the two identified as a muon. To ensure good particle identification and energy measurement, muons were required to have an energy greater than 2.0 GeV; an energy greater than 10.0 GeV was required for electrons or hadrons. (The latter cut eliminated the low-energy pions associated with resonance production.) The reconstructed two-track decay vertex was required to be at least 1 m from any material in the drift chambers.

The kinematic cuts were designed to remove the remaining DIS and resonance backgrounds. The effective scaling variables $x_{\rm eff}$ and $W_{\rm eff}$ were calculated for each event under the following assumptions: 1) the event was a neutrino charged current interaction ($\nu N \to \mu N' X$); 2) the highest energy identified muon was the outgoing particle from the lepton vertex; and 3) the missing transverse momentum in the event was carried by an undetected final state nucleon. Specifically, $x_{\rm eff} \equiv \frac{Q^2_{\rm vis}}{2m_p\nu_{vis}}$ and $W_{\rm eff} \equiv \sqrt{m_p^2 + 2m_p\nu_{\rm vis} - Q^2_{\rm vis}}$, where $Q^2_{\rm vis}$ is the reconstructed momentum transfer squared, m_p is the mass of the proton, and $\nu_{\rm vis}$ is the reconstructed hadron energy. Requiring $x_{\rm eff} < 0.1$ and reduced backgrounds from DIS; requiring $W_{\rm eff} > 2.0$ GeV removed quasielestic and resonance backgrounds. Since we could not reconstruct the true mass of the NHL due to the missing neutrino, a cut was applied on the "transverse mass," $m_T \equiv |p_T| + \sqrt{p_T^2 + m_V^2}$. p_T is the component of the total momentum perpendicular to the beam direction, and m_V is the invariant mass for the two charged tracks. Requiring $m_T < 3.0$ GeV removed additional DIS background.

The NHL and background acceptances and reconstruction efficiencies were calculated from the hit-level Monte Carlo simulation. For a range of NHL masses from 0.25 to 2.0 GeV, mesons were allowed to decay in the beamline to muons and NHLs. The NHLs from these decays were propagated to the decay channel, weighted by their decay and the meson production probability, and allowed to decay in the decay channel producing hits in the drift chambers and energy deposition in the Lab E calorimeter scintillation counters. These simulated raw data were reconstructed with the same programs used for the data including the above reconstruction and kinematic cuts. For NHL decays generated within the decay channel fiducial volume, the average acceptance was 23% for masses between 0.25 and 2.0 GeV. From the background simulation, the calculated background contributions for the full data sample after cuts are listed in Table I.

Neutrino events in the drift chambers and DIS (>2 track) events in the helium have been used to cross check the Monte Carlo calculations of backgrounds and efficiencies. For example, as a check on the two-track reconstuction efficiency, we have compared the fourteen two-track data events with vertices in the drift chambers to the Monte Carlo prediction of 15 $\pm$ 2 events. Figure 3 shows comparisons of distributions for the previously introduced DIS variables, $x_{\rm eff}$, $W_{\rm eff}$, $Q^2_{\rm eff}$ as well as m_T and $y_{\rm eff} \equiv \frac{E_\nu - E_\mu}{E_\nu}$. Data events with > 2 tracks also showed good agreement with the Monte Carlo prediction: 280 events were predicted, and 275 were observed.

For the full NuTeV data sample, no data events passed all cuts. This is consistent with the expected background of 0.57 ± 0.15 events. We have set limits from this null result by using the Monte Carlo prediction for $N_{\rm pred}(m_{\rm NHL}, |U|^2)$, the normalized number of NHL events expected in the decay channel as a function of mass and $|U|^2$. The 90% confidence level limit for a given mass was calculated for the null observation by finding the $|U|^2$ value for each mass such that $N_{\rm pred}(m_{\rm NHL}, |U|^2) = 2.3$ events.

The statistical 90% confidence level limit was modified by the addition of systematic uncertainties on the number of expected NHLs. These uncertainties are summarized in Table II. Experimental uncertainties on the D production cross section [5] and on the K meson flux Monte Carlo [4] were the dominant contributions to the systematic error. The systematic uncertainties were incorporated into the 90% confidence level limit by adding in quadrature a fractional error term corresponding to the systematic uncertainty for a given mass. Since the NHL rate was proportional to $|U|^4$, adding the systematic uncertainties increased the $|U|^2$ limit by 4%(14%) at 0.35(1.45) GeV.

Figure 4 shows the limits obtained from this search for the NHL-ν_μ mixing parameter $|U^2|$ as a function of the mass of the NHL. The limits are for NHL decay modes containing a muon in the standard mixing model presented above. Also shown in Fig. 4 are the results of previous experiments. [12–16]

In summary, we have made a sensitive search for NHLs in the mass range from 0.25 to 2.0 GeV that mix with muon neutrinos. No evidence for NHL production was observed. New limits have been set that are up to an order of magnitude better than previous searches in the lower mass range.

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TABLE I. Backgrounds to the NHL search.

background source description	number of events
ν interactions in the helium	0.56 ± 0.15
K^0 punch-through	0.005 ± 0.001
ν interactions in the material	0.002 ± 0.001

TABLE II. Systematic uncertainties on the sensitivity of the NHL search.

	NHL mass (GeV/c^2)		
Source	0.38	0.85	1.45
D production	-	44.6%	44.0%
K production	20.7%	-	-
D_S production	-	5.6%	5.4%
alignment	1.0%	0.4%	0.02%
resolution model	9.3%	7.0%	0.8%
reconstruction eff.	17.0%	19.1%	17.0%
TOTAL SYST.	28.4%	49.3%	47.5%

REFERENCES

[1] M. Gronau, C.N. Leung, and J.L. Rosner, *Phys. Rev.* **D29**, 2539 (1984).

[2] Particle Data Group, C. Caso *et al., Eur. Phys. J.* **C3**, 1 (1998).

[3] A. Malensek, FNAL-FN-341 (1981)

[4] D.C. Carey, K.L. Brown, F.C. Iselin, SLAC-0246 (1982).

[5] R. Ammar *et al., Phys. Rev. Lett.* **61**, 2185 (1988); K. Kodoma *et al., Phys. Lett.* **B263**, 573 (1991). (See also S. Frixione *et al., Nucl. Phys.* **B431**, 453 (1994).)

[6] J.A. Formaggio *et al., Phys. Rev.* **D57**, 7037 (1998) .

[7] L.M. Johnson, D.W. McKay, and T. Bolton, *Phys. Rev.* **D56**, 2970 (1997).

[8] W. Sakumoto *et al., Nucl. Instr. Meth.* **A294**, 179 (1990).

[9] R. Belusevic and D. Rein, *Phys. Rev.* **D38**, 2753 (1988).

[10] G. Ingelman *et al., Comput. Phys. Commun.* **101**, 108 (1997).

[11] CERN CN/ASD, GEANT detector description and simulation library (1998).

[12] S.R. Mishra *et al., Phys. Rev. Lett.* **59**, 1397 (1987).

[13] A.M. Cooper-Sarkar *et al., Phys. Lett.* **B160**, 207 (1985).

[14] J. Dorenbosch *et al., Phys. Lett.* **B166**, 473 (1986).

[15] T. Yamazaki *et al.,* in *Proc. Neutrino 84* (Word Scientific, Singapore, 1985).

[16] C.Y. Pang *et al., Phys. Rev.* **D8**, 1989 (1973).

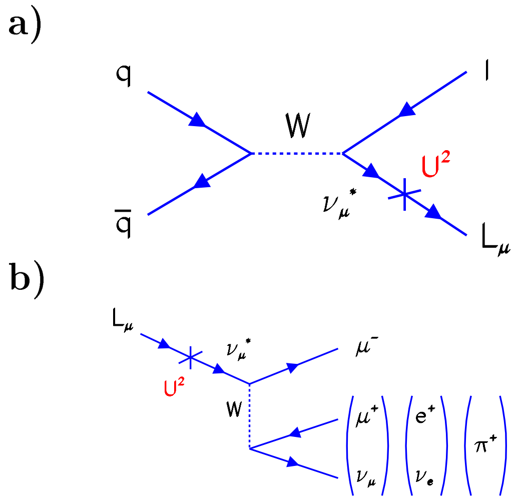

FIG. 1. Feynman diagrams for the (a) production and (b) decay of neutral heavy leptons (L_μ). $|U|^2$ is the mixing between the muon neutrino and the NHL. (The alternative allowed decay via a Z boson is not shown.)

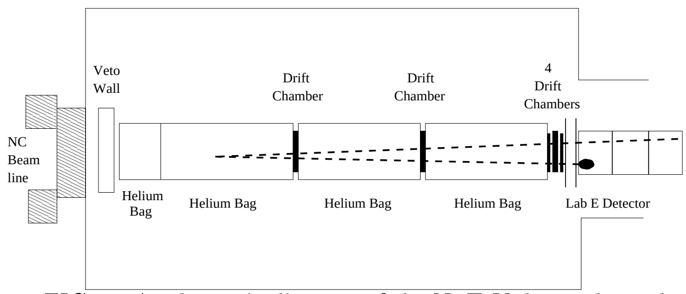

FIG. 2. A schematic diagram of the NuTeV decay channel. The beam enters from the left; at the far right is the Lab E calorimeter. An example NHL decay to $\mu\pi$ is also shown. The event appears as two tracks in the decay channel, and a long muon track and a hadronic shower in the calorimeter.

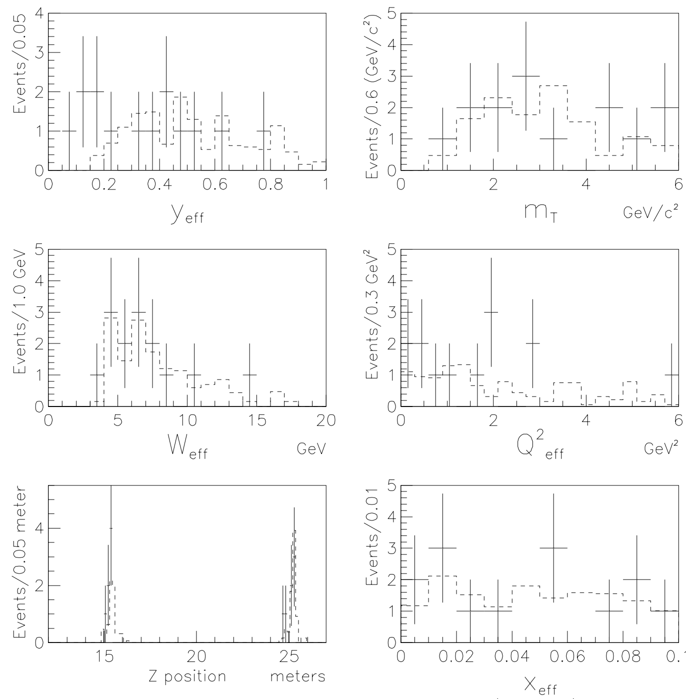

FIG. 3. Kinematic distributions for data (crosses) and MC DIS background (dashed) events with two-track vertices reconstructed in the decay channel drift chambers. MC events are absolutely normalized to the number of protons on target. The DIS reconstructed variables $y_{\rm eff}$, $W_{\rm eff}$, $Q^2_{\rm eff}$, $x_{\rm eff}$ and m_T are defined in the text. Z positions are referenced to the veto array; spikes in the Z distribution correspond to the locations of the decay channel drift chambers.

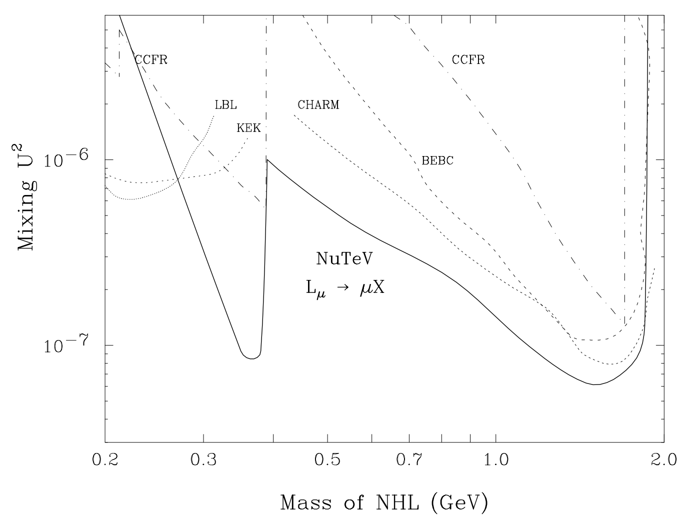

FIG. 4. NuTeV 90% confidence level limit for U_μ^2, the mixing of NHLs to Standard Model left-handed muon neutrinos, as a function of NHL mass. The solid line in the figure corresponds to the limit with systematic errors included.