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SEARCHING HIGH AND LOW FOR EXOTIC PARTICLES AT NUTEV

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The E815 (NuTeV) neutrino experiment at Fermilab has conducted two direct searches for neutral heavy leptons by using a dedicated instrumented decay channel. The first search probed the existence of neutral heavy leptons possessing masses between 0.3 and 2.0 GeV which decay into a muonic final state. The second was a specific search for a 33.9 MeV/c^2 neutral particle produced from pion decay. The latter directly addressed the timing anomaly reported by the KARMEN neutrino experiment. Results of both searches were presented at the Moriond Electroweak conference.

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1 Theoretical and Experimental Motivation

The search for the existence of neutral heavy leptons continues to be a prominent area of research in high energy physics. Neutral heavy leptons (NHLs) are plausible extensions to the Standard Model [1,2]. In several models, the neutral heavy leptons are considered heavy isosinglets that interact and decay by mixing with their lighter neutrino counterparts. Any intense source of neutrinos could therefore also be a potential source of neutral heavy leptons. All neutral heavy leptons produced in a neutrino beam would subsequently decay to leptonic or semi-leptonic states (i.e., $\mu\mu\nu$, $\mu e\nu$, or $\mu\pi$), which could then be detected. The number of neutral heavy leptons a typical experiment could produce and detect depends on two natural parameters: the mixing parameter (U^2) of the NHL and its mass. In general, a neutral heavy lepton may mix with each of the weak neutrino flavors with independent parameters $U_e, U_\mu, andU_\tau$. The high-intensity neutrino beam available at NuTeV is an ideal place to search for such exotic particles.

In addition to the theoretical motivation mentioned above, there also exists experimental motivation to search for these exotic decays. The KARMEN neutrino experiment has for the past several years reported an anomaly in the timing distribution of neutrino interactions from stopped muon decays [3,4]. One possible explanation for the anomaly is an exotic pion decay, where a neutral weakly-interacting or sterile particle is produced and travels 17.7 m to the KARMEN detector with a velocity of 4.9 m/μs. Upon reaching the KARMEN detector, the exotic particle decays to a partially electromagnetic state, such as $e^+e^-\nu$ or $\gamma\nu$. This slow moving exotic particle (hereafter denoted as Q^0) would have a mass of 33.9 MeV/c^2, which is near the kinematic threshold for $\pi \to \mu Q^0$ decay. Proposed explanations for the timing anomaly include neutral heavy leptons [5,6] and light neutralinos [7]. The KARMEN experiment reports a signal curve for pion branching ratio $B(\pi \to \mu + Q^0) \cdot B(Q^0 \to \text{visible})$ versus lifetime (see Fig. 2). Certain portions of the KARMEN signal have already been excluded; nevertheless, large fractions of the KARMEN allowed signal region still remain to be addressed.

2 The NuTeV Experiment

The E815 (NuTeV) neutrino experiment at Fermilab has performed a direct search for Q^0 and muonically decaying NHLs of exotic neutral particles by combining the capabilities of a high intensity neutrino beam with an instrumented decay region (the "decay channel"). During the 1996-1997 fixed target run at Fermilab, NuTeV received 2.54×10^{18} 800 GeV protons striking a BeO target with the detector configured for this search. The secondary pions and kaons produced from the interaction were subsequently sign-selected using a series of magnets and focused down a beamline at a 7.8 mr angle from the primary proton beam direction. The pions and kaons could then decay in a 440 m pipe producing neutrinos. In addition to pions and kaons, charmed meson decay could also contribute as a potential source of exotic neutral particles. The neutral weakly-interacting decay products traveled through approximately 900 meters of earth berm shielding before arriving at the decay channel.

The instrumented decay channel consisted of a series of helium bags, extending a total of 34 meters in length, interspersed with 3 m × 3 m multi-wire argon-ethane drift chambers. The drift chambers were designed to track charged particles from decays occurring within the helium. Upstream of the decay channel stood a 4.6 m × 4.6 m array of scintillation plates, known as the veto wall, used to detect any charged particles entering from upstream of the detector. Downstream of the decay channel was the Lab E neutrino detector, which consisted of a 690-ton iron-scintillator sampling calorimeter interspersed with drift chambers. The Lab E detector provided triggering, energy measurement, and final particle identification for tracks entering from the decay channel. Particles were identified by their penetration into the calorimeter: a muon produced a long track, a pion produced an elongated cluster of hits, and an electron or photon produced a compact cluster. More details of the decay channel and the calorimeter can be found elsewhere [8].

Table 1: Kinematic Requirements.

Variable	Requirement for NHL Analysis	Requirement for Q^0 Analysis
Particle Type	$\mu\mu$, μe, or $\mu\pi$	ee
Transverse Mass	$0.3 < m_T < 3.0$ GeV	$m_T < 0.25$ GeV
Total Visible Energy	$E_{vis} > 12$ GeV	$E_{vis} > 15$ GeV
X_{eff}	$X_{eff} < 0.1$	$X_{eff} < 0.001$
W_{eff}	$W_{eff} > 2.5$ GeV	$W_{eff} > 2.5$ GeV
Vertex Near Chambers Removed	Yes	No
Final Efficiency	23%	15%

3 Data Selection

A series of analysis cuts isolated the NHLs and Q^0's from background. For both analyses, the imposed requirements were very similar in structure. The cuts were subdivided into two general categories: reconstruction and kinematic. Reconstruction cuts isolated two track events occurring within the fiducial volume of the decay channel. We required that two charged tracks originated from a common vertex, with no additional tracks associated with the vertex. By removing events with activity in the veto wall, we ensured that no charged tracks entered from upstream of the decay channel. We also required that each track had a small slope relative to the beam axis, to aid the removal cosmic rays. Finally, we required that each track be identified as a muon, electron, or pion based on the shower shape apparent on the calorimeter. In our search for high-mass neutral heavy leptons, we required the two particles to be identified as a $\mu\mu$, a μe, or a $\mu\pi$ pair. In our search for the Q^0, we required the two tracks be identified as an electron pair.

Both the Q^0 and heavier NHLs possess kinematic features which can be used to distinguish them from potential background sources, such as photons and deep-inelastic neutrino interactions. We have used effective scaling variables to represent the kinematics of the reconstructed events. The effective scaling variables $x_{\rm eff}$ and $W_{\rm eff}$ were calculated for each event using the following assumptions: 1) the event was a charged current neutrino interaction ($\nu_\ell N \to \ell N'X$) and 2) the missing transverse momentum in the event was carried by an undetected final state nucleon. We have defined $x_{\rm eff} \equiv \frac{Q^2_{\rm vis}}{2m_p\nu_{\rm vis}}$ and $W_{\rm eff} \equiv \sqrt{m_p^2 + 2m_p\nu_{\rm vis}/c^2 - Q^2_{\rm vis}/c^2}$, where $Q_{\rm vis}$ is the visible reconstructed 4-momentum transfer, $\nu_{\rm vis}$ is the reconstructed hadron (or electron) energy, and m_p is the proton mass. The specific requirements using these kinematic variables imposed on the two analyses are shown in Table 1. In addition, our high mass search also required that the vertex occur at least 40 inches away from any drift chamber. This requirement was not used for the lower mass Q^0 search due to the poor longitudinal position resolution ($\sigma \approx 7m$) caused by the small opening angle of the electron tracks. The final efficiencies for both the high-mass NHL search and the Q^0 search were 23% and 15% respectively.

4 Backgrounds and Systematic Checks

The principal backgrounds originated from three sources: neutrino interactions in the helium, neutrino interactions in the drift chambers, and neutral particles (mainly photons and kaons) from neutrino interactions in the berm and veto wall. A list of all backgrounds, after all kinematic and reconstruction cuts have been applied, can be seen in Table 2. The total number of background events expected for the high mass signal region was 0.58 ± 0.15. The total number of background events expected in the Q^0 signal region was 0.06 ± 0.05.

Before examining the data near or in the signal region, we performed a series of studies to verify our background estimates. Using the Monte Carlo, we made predictions for the following three quantities: 1) the number of low energy (below 15 GeV) and high transverse mass (above 500 MeV/c^2) background

Table 2: Total Expected Background Events.

Source	Events in NHL Signal Region	Events in Q^0 Signal Region
Photons	$0.04 \pm +0.02$	$\ll 0.01$
Kaons	$\ll 0.01$	$\ll 0.01$
Deep Inelastic Charged Current	0.00 ± 0.04	0.56 ± 0.15
Deep Inelastic Neutral Current	0.02 ± 0.02	$\ll 0.01$
Cosmic rays	$\ll 0.01$	0.01 ± 0.01
Quasi-Elastic Charged Current	$\ll 0.01$	$\ll 0.01$
Resonance Neutral Current	$\ll 0.01$	$\ll 0.01$
Diffractive Pions	0.00 ± 0.01	0.00 ± 0.01
Total	0.06 ± 0.05	0.58 ± 0.15

Table 3: Background Study Results. Uncertainties are systematic.

Type of Event	Events Predicted	Events Seen
High Transverse Mass	2.0 ± 0.3	1
$\mu\pi$ Events	4.1 ± 0.6	3
Multiple Track Events	13.7 ± 1.8	10

events; 2) the number of $\mu\pi$ events; and 3) the number of multi-track events occurring within our decay channel. The results of these studies (shown in Table 3) demonstrate good agreement between data and the Monte Carlo predictions. In the case of multi-track events, where a larger sample of events was available, there was also good agreement for various kinematic distributions (Fig. 1).

5 Results

In both searches, no events were found in the signal region. It is thus possible to set a limit on the existence of NHLs and Q^0's [9,10]. In both cases, the limits are a significant improvement over previous experiments. Notably, the Q^0 result improves limits by 4 orders of magnitude for small lifetimes. Limits for each search are shown in Fig. 2 and Fig. 3

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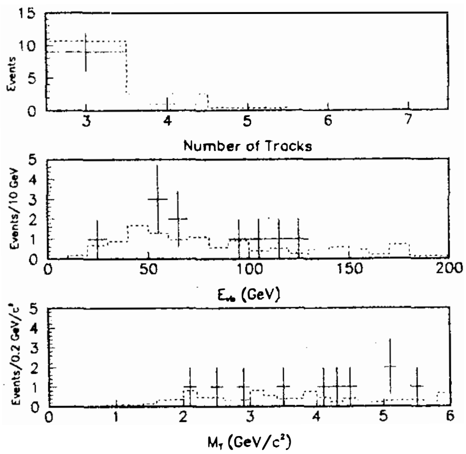

Figure 1: Kinematic distributions of multiplicity, energy, and transverse mass for data (crosses) and background Monte Carlo (dashed) multi-track events. Monte Carlo is absolutely normalized.

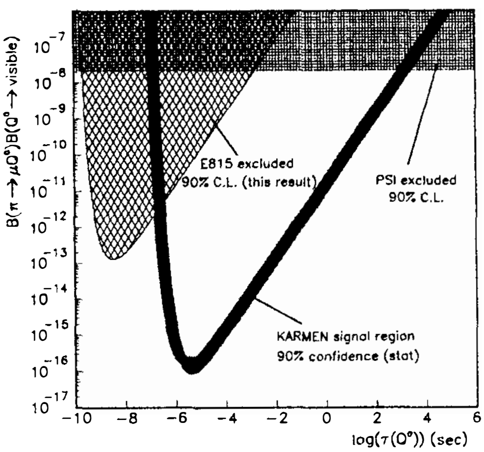

Figure 2: Q^0 branching ratio versus lifetime plot for the KARMEN signal and the exclusion regions (90% C.L.) from the NuTeV and PSI experiments. Systematic errors (except for decay model) have been included.

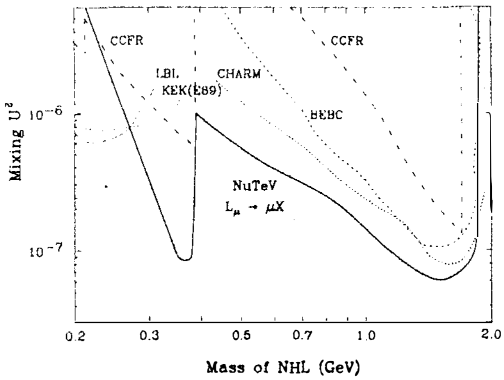

Figure 3: NHL limit at 90% confidence level for U_μ^2 as a function of mass. Systematic errors are included.

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