AN UPPER LIMIT ON THE ELECTRON-NEUTRINO FLUX FROM THE HiRes DETECTOR

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ABSTRACT

Air-fluorescence detectors such as the High Resolution Fly’s Eye (HiRes) detector are very sensitive to upward-going, Earth-skimming ultra-high-energy electron-neutrino-induced showers. This is due to the relatively large interaction cross sections of these high-energy neutrinos and to the Landau-Pomeranchuk-Migdal (LPM) effect. The LPM effect causes a significant decrease in the cross sections for bremsstrahlung and pair production, allowing charged-current electron-neutrino-induced showers occurring deep in the Earth’s crust to be detectable as they exit the Earth into the atmosphere. A search for upward-going neutrino-induced showers in the HiRes-II monocular data set has yielded a null result. From an LPM calculation of the energy spectrum of charged particles as a function of primary energy and depth for electron-induced showers in rock, we calculate the shape of the resulting profile of these showers in air. We describe a full detector Monte Carlo simulation to determine the detector response to upward-going electron-neutrino-induced cascades and present an upper limit on the flux of electron neutrinos.

Subject headings: acceleration of particles — cosmic rays — large-scale structure of universe — neutrinos

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1. INTRODUCTION

We report on a search for upward-going electron-neutrino showers in the High-Resolution Fly’s Eye II data set, and on the upper limit on the flux of $\nu_e$, set by the HiRes-II detector. The HiRes project has been discussed previously (Abu-Zayyad et al. 1999; Boyer et al. 2002); the detector is an air-fluorescence detector located on two sites 12.6 km apart in Utah at the US Army Dugway Proving Ground. The HiRes-II detector, located on Camel’s Back Ridge, is composed of 42 spherical mirrors of 3.7 m$^2$ effective area covering nearly 360° in azimuth. Half of these, known as ring-one mirrors, cover between 3° and 17° in elevation; the other half (ring-two) cover between 17° and 31° in elevation.

Cosmogenic neutrinos, with energies mostly in excess of 10$^{18}$ eV, are produced via $\pi$ and $\mu$ decays following photopion production from high-energy cosmic-ray protons incident on the cosmic microwave background radiation (Stecker 1968; Margolis et al. 1978). There is evidence to suggest that gamma-ray bursts and active galactic nuclei jets are possible sources of high-energy cosmic rays and neutrinos (Waxman & Bahcall 1997; Halzen & Zas 1997). Several theoretical limits on the flux of cosmogenic neutrinos have been proposed (Semikoz & Sigl 2004; Seckel & Stanev 2005).

Although large uncertainties exist, neutrino cross sections have been calculated to vary from $\sim 10^{-32}$ cm$^2$ at 10$^{18}$ eV to $\sim 10^{-31}$ cm$^2$ at 10$^{21}$ eV (Reno 2005). The opacity of the Earth to neutrinos at these high energies therefore prohibits the detection of any upward-going event with an elevation angle larger than a few degrees.

In the charged-current interaction of a $\nu_e$, in the Earth’s crust, a high-energy electron will be created. The electromagnetic cascade generated by the electron will develop much more slowly due to the onset of the Landau-Pomeranchuk-Migdal (LPM) effect. The LPM effect, first described classically by Landau & Pomeranchuk (1953) and later given a quantum-mechanical treatment by Migdal (1956), predicts that the cross sections for bremsstrahlung and pair-production should decrease for a high-energy charged particle propagating in a dense medium, effectively slowing and elongating the development of the resulting shower of particles (a detailed, more modern approach can be found in Takahashi et al. [2003] and Bai & Katkov [2004]). The energy at which this effect becomes appreciable is inversely proportional to the square of the Lorentz factor $\gamma$, and therefore the LPM effect should be much more pronounced for the showers generated from a $\nu_e$ charged-current interaction than for showers precipitated by $\nu_\mu$ or $\nu_\tau$ in the energy range in which HiRes is sensitive.

It is most probable that a neutrino-induced electromagnetic cascade would be long and nearly horizontal, and observed primarily in the HiRes-II ring-one mirrors. Due to the LPM effect, one expects electron-neutrino-induced showers that begin several tens to hundreds of meters deep in the crust to emerge with enough
charged particles to be detected by HiRes-II, thereby increasing
the effective aperture of the detector at high energies.

2. SEARCH FOR UPWARD-GOING NEUTRINO EVENTS

The entire HiRes-II data set, which extends from late 1999 to
Spring 2006, was considered when searching for evidence of
neutrino-induced upward-going showers. Using the standard rou-
tines that were developed for analyzing downward-going cosmic-
ray events, we reconstructed the trajectories of each upward-going
event based on the measured timing and geometry (see Sokolsky
[1989] for a description of time- and plane-fitting for extensive
air showers).

The data were then filtered in time and position to exclude all
calibration laser events, which resulted in a loss in the detector
aperture of less than 1%. In addition, and consistent with stan-
dard procedure for the analysis of cosmic-ray data, events were
rejected that passed within 100 m of the detector, had track lengths
smaller than 10°, and that had geometrical uncertainties from
timing greater than 36°.

3. THE LANDAU-POMERANCHUK-MIGDAL EFFECT

At electron energies below the LPM threshold energy (61.5 ± 15
TeV [Staney et al. 1982], where \( L_{\text{em}} \) is the interaction length in cm),
the longitudinal profile of an electromagnetic shower can be well
approximated by the relation

\[
N(t) = \frac{0.31}{\beta_0^{1/2}} \exp \left[ \frac{t}{1 - \frac{3}{2} \ln s} \right].
\]

This functional form was first described by Greisen (1956), with \( \beta_0 \) as the log of the ratio of the energy of the incident electron to
its critical energy \( E_c \), \( t \) as the depth in radiation lengths, and
\( s = 3t/(t + 2.30) \).

This relation begins to break down at high energies, greatly un-
derestimating the distance over which the electromagnetic cascade
evolves due to the decrease in the cross sections for bremsstrahlung and \( e^+e^- \) pair production. Studies of the electron shower profiles
in rock, water, and lead above the LPM threshold energy have been
conducted previously (Misaki 1990; Staney et al. 1982; Alvarez-
Muñiz 1999). As expected, the results of these analyses show that
the shower profiles of electron-induced cascades are significantly
elargated with respect to the Greisen approximation at energies
above the LPM threshold, and evolve differently based on the
densities of the media in which the showers propagate.

4. CALCULATION OF SENSITIVITY
   TO ELECTRON-NEUTRINO SHOWERS

To simulate \( \nu_e \)-induced electromagnetic cascades, we used a four-
step process. First, we calculated the average profiles of electron-
induced showers using the LPM effect. We then used a Monte
Carlo method to simulate the arrival directions and interaction
points of \( \nu_e \) around the HiRes detector. The shower profiles in air
were then passed into the HiRes detector Monte Carlo to calculate
the amount of light seen by the detector. The HiRes analysis
programs were then run on the resulting Monte Carlo events to
arrive at a \( \nu_e \) aperture.

4.1. Calculating Electron-Neutrino-Induced
   Electromagnetic Cascade Profiles

In order to treat charged-current \( \nu_e N \) interactions in the Earth’s
crust, it is necessary to understand the physics of the transition of
an electromagnetic cascade from a dense medium to a less dense
medium (namely, from rock to air). It is therefore important to
know not only the number of charged particles after traversal of a
given amount of material in rock, but also the energy spectrum of
these particles as they leave the ground and enter the atmosphere.

We followed the formalism of Staney et al. (1982) for calculat-
ing the energy dependence of the probabilities for undergoing pair
production and bremsstrahlung at LPM energies. Taking into
account any other losses (e.g., Compton scattering and ionization
energy loss), we calculated two functions: \( N^{\text{rock}}_e(E_0, E, d) \) and
\( N^{\text{air}}_e(E_0, E, d) \), which describe the average number of charged
particles with energy \( E \) resulting from the cascade of an electron,
positron, or photon with initial energy \( E_0 \) after traversing an amount
of material \( X \) in rock or air. The functions \( N^{\text{rock}}_e \) and \( N^{\text{air}}_e \) were
determined for \( E_0 \) at every decade between 10^{12} and 10^{21} eV using
our LPM calculation and from \( E_0 \) to 10^{12} eV using equation (1);
LPM calculations of shower profiles from particles with initial
energies below 10^{12} eV were found to be nearly identical to
profiles calculated using equation (1).

4.2. Simulating Neutrino Events

We approximated the Earth as a sphere with a radius equal to
that at the Dugway Proving Ground in Utah. The density below
58.4 km beneath the surface (mantle) and the density from 58.4 km
to the surface (crust) were taken to be 4.60 and 2.80 g cm^{-3},
respectively. The atmosphere was also simulated up to a height
of 50 km above sea level.

Electron-neutrino energies were considered from log \( E_x \) of 18
to 21. The energy dependence and inelasticity of the charged and
neutral current \( \nu N \) interaction cross sections were calculated based
on the pQCD CTEQ5 model (Lai et al. 2000; Gazizov & Kowalski
2005). From the ratio of the cross sections for charged-current
(CC) and neutral-current (NC) interactions, 70% of the events
were thrown as CC events, while the remaining 30% were con-
sidered NC events.

Neutrino arrival directions were chosen at random such that
they only penetrated the atmosphere no more than 15° below the
horizon. Events with elevation angles greater than 15° do not
contribute appreciably to the HiRes-II total \( \nu_e \) aperture due to the
very small probability of their transmission through the crust and
mantle and subsequent interaction near the detector. We approximated
at 15° has a probability of \( \sim 10^{-12} \) of transmission and inter-
action near the detector; this value drops to \( \sim 10^{-60} \) at 10^{21} eV). The
variables describing the geometry of the neutrino trajectory
were determined, such as the distance of closest approach to the
detector, the vector normal to the shower-detector plane, and the
angle of the shower in the shower-detector plane.

For these Earth-skimming events, the traversal of a critical
amount of material \( X_e \) (measured in g cm^{-2}) was found such that
when the shower emerges from the rock into air, it contains at
least 10^{12} charged particles; showers with a maximum number of
charged particles less than 10^{7} will not trigger the HiRes detector.
This critical path length is used to separate the probabilities for
neutrino transmission and interaction. The transmission probabil-
ity \( \epsilon_e \) was calculated as the probability for a neutrino to penetrate
up to \( X_e \). The interaction probability \( \epsilon_i \) was calculated from the
path length of the neutrino from \( X_e \) until escape from the atmo-
sphere. Since the amount of material traversed in the interaction
region is always much less than the mean neutrino interaction
length, the actual point of interaction for each neutrino was then
chosen at random for distances \( X \geq X_e \). For neutrinos with small
0 elevation angles that do not pass through the Earth, we considered
events that entered the atmosphere above the horizon as well as
those that interacted below the horizon and yielded at least \(10^7\) particles at the horizon. For events interacting below the horizon, \(X_e\) was taken to be the amount of air penetrated at the horizon. In the case of events that entered the atmosphere above the horizon, we set \(e_{\nu}\) to unity and calculated \(e_i\) from the total distance traversed in the atmosphere.

For all \(\nu_e N\) interactions, the energy transferred to the secondary electron or hadron was chosen from the inelasticity distribution \((d\sigma/dy)\) for the pQCD CTEQ5 model. For earth-skimming CC events, the resulting observable profile in air was found from a superposition of showers obtained from the energy spectrum of electrons, positrons, and photons emerging from the rock. The profiles of CC events that did not pass through the Earth were interpolated from the \(N_{\text{air}}\) functions described in the previous section. The profiles for all NC events were calculated using the standard Gaisser-Hillas model (Gaisser 1990). Each profile was then weighted by a factor \(w = e_{\nu}e_i\), to describe the total probability of transmission and interaction near HiRes-II. Figure 1 shows the average profiles of five electron-induced air showers emerging from the ground at different depths along an average \(10^{20}\) eV electron-induced shower in rock.

### 4.3. Simulating Detection by HiRes

Having generated shower profiles using the LPM effect, the shower profiles were then passed through a HiRes Monte Carlo program, which models the response of the detector to cosmic-ray-induced showers. This program determines the amount of fluorescence and Čerenkov photons produced for a given number of charged particles, and scatters and attenuates the light appropriately when given the known variables describing the geometry of the shower with respect to the detector. The program then models the HiRes-II trigger conditions to decide if the simulated shower is read out by the detector (Abbasi et al. 2004).

### 4.4. Analysis and Filtering of Simulated Events

Simulated showers which triggered the detector were analyzed with the same routines used in the analysis of the real data in our search for neutrinos in the upward-going HiRes-II data. The variables describing the geometry of the shower were fit and compared to the known variables. An event was considered accepted when it passed the cuts described in §2.

### 5. Calculating an Electron-Neutrino Flux Upper Limit

For the purposes of arriving at a predicted HiRes-II \(\nu_e\) aperture, the simulated events were collected in 30.1 decade energy bins from \(10^{15}\) to \(10^{21}\) eV. The aperture for a given energy bin was found to be

\[
(A\Omega)_E = \left[ 2\pi \int_0^{\frac{\pi}{2}} \sin(\theta) d\theta \right] R^2 \left( \sum_{i} \frac{N_e w_i}{N_T} \right)_E,
\]

where \(R\) is the radius of the Earth extended 50 km to the edge of the atmosphere. The geometrical component of the aperture is derived from the area and solid angle of a \(30^\circ\) cap on a sphere of radius \(R\). This is then adjusted by the weighting factor \(w\) (discussed in §4.2) for each of the \(N_e\) events that trigger the detector, out of a total \(N_T\) events thrown in the given energy bin. The HiRes-II \(\nu_e\) aperture is shown in Figure 2.

Consistent with our study of \(\nu_e\) (Martens et al. 2007), we calculate a flux limit in three energy bins, \(\Delta E = 10^{18} - 10^{19}, 10^{19} - 10^{20},\) and \(10^{20} - 10^{21}\) eV, over the total HiRes lifetime of 3638 hr. We observe no neutrino events over the entire energy range. We calculate the flux limit \(E^2 dN/dE)\) at the 90% confidence level to be \(4.06 \times 10^{3}, 3.55 \times 10^{3},\) and \(4.86 \times 10^{3}\) eV cm\(^{-2}\)sr\(^{-1}\)s\(^{-1}\) at \(10^{18.5}, 10^{19.5},\) and \(10^{20.5}\) eV, respectively. Combined with our \(\nu_e\) results and provided equal mixing of all neutrino flavors, this reduces the limit to \(3.81 \times 10^{2}, 9.73 \times 10^{3},\) and \(4.71 \times 10^{3}\) eV cm\(^{-2}\)sr\(^{-1}\)s\(^{-1}\).

### 6. Discussion

As is the case with all high-energy neutrino calculations, the largest uncertainty lies in the extrapolation of \(\nu/N\) cross sections. Different cross section models can cause the limits to vary somewhat. The incorporation of cross sections from previous and more recent versions of the CTEQ model can change the limits by as much as 10% to 40% at the lowest and highest energies, respectively.

Recent work imposing the Froissart bound on structure functions for extrapolating \(\nu/N\) cross sections show a decrease in cross sections at \(10^{21}\) eV by about a factor of 8 over the CTEQ5 parameterization (M. M. Block 2007, private communication). These cross sections increase our \(\nu_e\) limit by 40% at the lowest energy bin and increase the value of our highest energy bin by a factor of 3.
In addition to uncertainties in $\nu/N$ cross sections, our limits are also sensitive to the energy transferred to the secondary electron or hadron. From parameterizations of the mean inelasticity in $\nu/N$ interactions (Quigg et al. 1986), if we allow the transfer of exactly 80% of the neutrino energy to the electron (and 20% to the hadron), our $\nu_e$ limits will increase about 15% at $10^{18.5}$ eV, remain unchanged in the middle energy bin, and decrease by about 5% at $10^{21.5}$ eV.

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