HiRes Estimates and Limits for Neutrino Fluxes at the Highest Energies

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The High Resolution Fly’s Eye Experiment (HiRes) measures cosmic rays (CR) at the highest energies using the air fluorescence technique. As data taking on the Dugway Proving Grounds in Western Utah is finished, the HiRes data are relevant for cosmogenic neutrinos in two different ways. We first use our best fit to the measured HiRes CR spectrum together with a model of the extragalactic CR sources to derive the expected cosmogenic neutrino and gamma ray fluxes at Earth. We then use the HiRes data directly to set competitive experimental limits on the electron and tau neutrino fluxes at the highest energies.

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1 Introduction

Cosmogenic neutrinos are neutrinos generated by cosmic rays (CR) as they propagate over cosmological distances and lose energy in interactions on various photon backgrounds. Excitation of the $\Delta^+$ resonance in protons moving through the Cosmic Microwave Background (CMB) will start for proton energies above $\sim 6 \times 10^{19}$ eV, leading to the expectation that these protons will arrive at earth with energies diminished by this energy loss process. The resulting feature at the end of the CR power law spectrum is called the GZK cutoff after the authors who first pointed out this theoretical limit to the reach of a protonic CR spectrum: Greisen, Zatzezin, and Kuzmin [1]. With the GZK feature evident in the HiRes monocular spectra [2], and with the Auger CR spectrum in good agreement with HiRes at the relevant energies, there now is a strong case for the existence of cosmogenic neutrinos.

This interpretation of the CR spectrum hinges on the assumption that the extragalactic CRs at the highest energies are protonic in nature. While composition studies for CR do not reach up to the highest energies yet, HiRes has measured the composition up to $2.5 \times 10^{19}$, concluding that at the highest energies the CR indeed are mostly protons [3].
2 The HiRes Detector

The HiRes experiment consists of two detector sites located 12.6 km apart that each monitor the surrounding sky for fluorescence emission from extensive air showers. On clear, moonless nights individual telescopes continuously survey a patch of the sky that measures roughly 16 degree along the horizon and 14 degree in elevation. 256 photomultiplier tubes per telescope allow a pixelisation with a pixel size of 1 degree in the sky. If all telescopes are taking data, both detectors achieve nearly full coverage in azimuth. HiRes 1 (HR1) has 22 telescopes viewing the elevation band from 3 degree above the horizon to 17 degree above the horizon. It is equipped with sample-and-hold electronics that record the threshold crossing time for each pixel and a charge integral over 3.6 µs. HiRes 2 (HR2) has 42 mirrors that cover elevations from 3 to 33 degree. It is equipped with flash-ADC electronics that trace the signal evolution for every pixel with 100 ns resolution over 10 µs.

3 Neutrino and Gamma Ray Fluxes Expected from the HiRes Monocular Spectra

The HiRes detector was developed for stereoscopic observation of extensive air showers (EAS) by means of their fluorescence emission. The restriction to stereoscopically seen EAS limits the HiRes aperture in two important ways: At the highest energies detector lifetime is most important, and using older equipment HR1 was operational for almost 4 years before HR2 became operational to allow stereoscopic observation. At the lower energies the reduced fluorescence light output of the lower energy EAS forces us to rely on the HR2 monocular observations as HR2 has higher elevation coverage and can thus capture the shower maximum even for close-by EAS. For these reasons the monocular spectra of the two HiRes detectors will always be superior in statistics and, most important for spectrum fits, span a wider range of energies than the stereo spectrum.

Building on work of Doug Bergman at Rutgers [4], we calculate the neutrino and gamma ray spectra expected due to the propagation of protons from their hypothetical source population to Earth. The CR spectrum as measured by HiRes detectors in monocular mode is used to constrain the model of astrophysical proton sources. Protons emitted at the source undergo interactions with the CMB that excite the $\Delta^+$ resonance or produce $e^+e^-$ pairs and are cooled down by the expansion of the universe along their way. All these processes are taken into account in calculating what the proton spectrum will be at earth by adding the respective contributions from redshifts out to 4.0 in steps of 0.01. The sources are all assumed to have the same universal injection spectrum of the form $E^{-\gamma}$, and $\gamma$ together with a universal normalization constant for this injection spectrum are two of the three free parameters used in fitting the HiRes CR spectra to this source model. The last parameter is an exponent $m$ in the form $(1 + z)^m$ that we assume for the evolution of this source population with redshift $z$. 10,000 protons are propagated through an evolving CMB for
each of our shells of 0.01 thickness in $z$.

As first pointed out by Berezinsky [5], this model reproduces well the features of the CR spectrum at the highest energies. The ankle in this context is excavated by the $e^+ e^−$ energy loss mechanism and does not mark the transition from galactic to extragalactic sources. This latter transition is marked by the disappearance of Fe nuclei from the composition at end of the galactic CR spectrum. Above about $10^{18}$ eV this transition from galactic to extragalactic CRs is completed as signalled by a change of slope in our composition measurement. In our fits to the HiRes CR spectrum we add a galactic component of Fe nuclei according to the fractional composition of the measured spectrum as suggested by our composition measurements.

The resulting best fit to the HiRes monocular CR spectrum is shown in Figure 1. It is obtained for $\gamma = 2.42$ and $m = 2.46$. In this fit the low energy region is most affected by changes in $\gamma$, whereas the high energy region reacts more strongly to changes in $m$. Future improvements to these fits will include a more realistic redshift evolution modelled after observations on suitable populations of Active Galactic Nuclei, the prime suspects in accelerating CR to the energies involved here. The spikes that appear at high energies in the fitted proton spectrum reflect our choice of stepsize in $z$. Future work will reduce this stepsize from its current value of 0.01 to arrive at a smoother distribution.

![Figure 1: The best fit to the HiRes monocular spectra propagating protons from extragalactic sources up to redshifts of 4. A component of iron nuclei is added as derived from HiRes composition measurements.](image-url)
Figures 2 and 3 show the respective neutrino and gamma ray fluxes at the highest energies resulting from CMB interactions of the propagating protons. The “low” energy hump in the electron neutrino spectrum originates from the neutron decay occurring if the $\Delta^+$ resonance decays into $n + \pi^+$. The structure in the gamma ray spectrum is carved out by interactions with the CMB of the gamma rays themselves as they propagate from their respective points of origin to Earth. The spikiness in the gamma ray spectrum near 10 TeV is an artefact of limited statistics.

![Graph showing neutrino and gamma ray fluxes](image)

Figure 2: Fluxes of electron (green) and muon (blue) neutrinos. The neutrinos are shown with their flavors at origin but their energies properly redshifted to Earth. The red proton spectrum is the one from the best fit and shown for reference.

4 Neutrino Flux Measurements with HiRes

Two different neutrino flux limits exist from the HiRes experiment. The first one exploits the fact that charged current tau neutrino interactions in the vast target mass of mountains and the Earth’s crust produce tau leptons that can escape into the atmosphere, where their decay may then produce an air shower that is visible to the HiRes detector. The second limit exploits the Landau, Pomeranchuk, Migdal (LPM) effect for electron neutrino induced electromagnetic showers in the earth and in the atmosphere.
Figure 3: Gamma ray fluxes for their energies upon arrival at Earth. The wiggles in the low energy bump are due to statistical limitations. The fate of the $e^+$ and $e^-$ produced in the CMB interactions of the photons that were lost in propagation is not followed up on and resulting secondary photon fluxes do not contribute to this spectrum.

5 Monte Carlo Simulation

Our Monte Carlo (MC) simulation of tau neutrino interaction and tau propagation and decay is based on the All Neutrino Interaction Generator (ANIS) [6]. ANIS incorporates a model of the earth interior with the appropriate density changes between inner and outer core and mantle. It offers two alternatives for the extrapolation of neutrino cross sections on nucleons: A smooth power-law extrapolation of pQCD CTEQ5 structure functions, and a hard pomeron enhanced extrapolation. The two differ by about a factor of three at $10^{20}$ eV. Our calculations were done with the lower cross section extrapolation that did not have the pomeron enhancement. As far as the cross sections are concerned our limit should therefore be conservative, but neutrino cross section extrapolation is the major systematic uncertainty in this analysis.

ANIS also incorporates code for the propagation and decay of the tau leptons. The intrinsically stochastic energy losses at high energy are approximated by a smooth energy loss function. For HiRes the ensuing suppression of potential sub-showers resulting from catastrophic energy loss events along the path of the tau lepton is not much of a concern, as the trigger threshold of the detector
even for very close events is above $10^{16}$ eV. Tau decays in ANIS are modeled with the TAUOLA package.

As ANIS was designed for underground detectors, it has neither an atmosphere nor any topographic structure on the earth surface built into it. We integrated both a US standard desert atmosphere \cite{7} and the detailed surface topography of the surroundings of the HiRes detectors. The elevation model we incorporated is based on a 30 arcsec grid \cite{8}.

Figure 4 is a scatter plot of the $\nu_\tau$ interaction points for $\nu_\tau$ where the ensuing tau lepton decays above ground. The figure clearly highlights the role of the surrounding mountains as target mass. It can also be seen that HR1 has greater proximity to the bulk of that target mass. While $\nu_\tau$ interactions in the atmosphere are not suppressed in this simulation, they do not play a role due to the limited target mass available.

A prominent feature of the tau leptons that emerge into the atmosphere is that their zenith angles are concentrated within a few degrees from horizontal. Figure 5 shows the distribution of zenith angles of the tau leptons that decay in the atmosphere. Zenith angles larger than 90 degree are upward going. We exploit this feature to constrain the neutrino injection directions to $\pm10$ degree above and below the local horizon, thus saving significant computing time in our simulations. We also limit the impact parameter of neutrino trajectories to within 75 km of the geometrical center between HR1 and HR2.

The tau leptons decay to 70% into hadronic decay channels. Charged pion initiated showers are used in the subsequent air shower simulation. In case a leptonic decay channel is entered, the ensuing lower energy tau is followed up upon, a muon is given up as unobservable, and an electron is fed into the appropriate electromagnetic shower simulation.

For the hadronic decays air shower simulation is carried out with the help of CORSIKA \cite{9} version 6.200. Shower libraries are generated using QGSJET \cite{10} that contain 400 quasi-horizontal hadronic showers each in a matrix of thirteen evenly spaced energies from $10^{15}$ eV to $10^{21}$ eV and nine evenly spaced heights between 1 km and 5 km above ground. After a suitable tau decay is identified in the ANIS output, a set of shower parameters is chosen randomly from the appropriate library, and scaled from the nearest energy found in the library to the energy extracted from the ANIS simulation. These shower parameters and the ANIS generated event location and direction are then handed over to the standard version of the HiRes stereo Detector Monte Carlo (DMC) program. If the tau lepton decays to an electron, the DMC itself generates the appropriate profile for an electromagnetic shower.

The DMC generates fluorescence (and Cherenkov) light according to the geometry and energy of the shower, propagates both through the atmosphere towards the detector, and performs a detailed simulation of the detector response.

494 M tau neutrinos with impact parameters up to 75 km were injected into ANIS. Their input energies were distributed between $10^{18}$ and $10^{21}$ eV according to an $E^{-2}$ differential spectrum. While there was no constraint on the azimuth angle of the neutrino injection, the zenith angle was constrained
to within ±10 degree of the horizon. From this input we got a total of 5829 events that triggered the detector: 4243 triggers in HR1, and 2456 in HR2. 870 of these events triggered both detectors.

Our electron neutrino simulation uses the same cross section extrapolation as the tau neutrino analysis. Using a spherically symmetric model of the earth with just one transition between the mantle with density 4.6 g/cm$^3$ and the crust with 2.8 g/cm$^3$ at 58.4 km below the surface the MC simulation is much more efficient as no terrain features break the symmetry. The LPM effect is implemented following the formalism of [11] to calculate the energy dependence for the probabilities to undergo bremsstrahlung or pair production.

6 HiRes Data and Analysis

The HR1 data used in this analysis stem from the equivalent of 20,132,360 seconds of operation with all HR1 mirrors and were taken between 05/1997 and 11/2005. The HR2 data were taken over the equivalent of 13,096,693 seconds of operation with all HR2 mirrors between 10/1999 and 11/2005. This data set includes 10,128,727 seconds of stereo operation. A total of 75 million data records were analyzed. In a first step noise events and artificial light sources are eliminated.

The relevant variables characterizing the EAS geometry are the zenith angle $\Theta$ and the impact parameter $R_p$ of the shower axis with respect to the relevant detector location.

Two defining characteristics identify our $\nu_\tau$ events:
- They are horizontal (zenith angle)
- They are low in the atmosphere ($R_p$ distance)

The last criterion is not trivial as very high up in the atmosphere CR events can develop almost horizontally. In order to reliably extract $\nu_\tau$ events we impose cuts on the quality of the event reconstruction. After these quality cuts and application of an $R_p < 20$ km cut events with reconstructed zenith angles between 88.8 and 95.1 degree (1.55 and 1.66 radians) are kept as neutrino candidates. With these cuts we keep 366 neutrino MC events in HR1 and 209 in HR2, out of which 21 are stereo events.

Applying the same criteria to the data yields 75 events from HR1 and 59 events from HR2. All of these 134 neutrino candidate events are unfortunately laser events. The reason that these events pass all our laser cuts have to do with weather: Light scattered off haze near the ground lets these particular events reconstruct as horizontal. Unlike true neutrino events their individual geometries can all be shown to repeat that of another event inside or outside of the set of selected neutrino candidates. Our conclusion is that HiRes has zero tau neutrino candidates.

Data analysis for the electron neutrino search is based on the superior reconstruction afforded by the HR2 detector’s flash ADC system, and therefore is restricted to events seen with the HR2 detector. As in the tau neutrino analysis no neutrino candidate events were found.
| \( \log_{10}(E/\text{eV}) \) | 18 - 19 | 19 - 20 | 20 - 21 |
|-----------------|---------|---------|---------|
| \( \nu_\tau \)  | \( 420^{+220}_{-20} \) | \( 1340^{+140}_{-110} \) | \( 29400^{+22100}_{-8900} \) |
| \( \nu_e \)     | \( 3820 \pm 120 \) | \( 3260 \pm 80 \) | \( 4250 \pm 100 \) |

Table 1: Fluxes excluded by HiRes at the 90% CL in units of eV sr\(^{-1}\)s\(^{-1}\)cm\(^{-2}\) for three energy ranges. The uncertainties derive from MC statistics only.

Our limits on neutrino fluxes are based on Feldman/Cousins unified confidence intervals and are listed in table 1 as well as shown in the context of other experimental results in figure 6.

7 Conclusions

Searching for near horizontal showers HiRes has set new competitive limits on cosmogenic neutrino fluxes. At \( 10^{19} \text{ eV} \) the tau lepton decay length (not counting energy losses) reaches 500 km, so that despite the growing cross section for neutrino interaction the subsequent tau lepton decay at higher energies increasingly is pushed beyond the physical limits of the atmosphere. LPM delayed electron neutrino showers do not have this handicap, leading to a competitive result at the highest energies. All of these limits are orders of magnitude above the flux expectation we derived from our cosmic ray spectrum.

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Figure 4: A map of the surroundings of the HiRes detectors made from the interaction points of tau neutrinos for which the tau leptons decay in the atmosphere. The mountains are visible in green, and two yellow dots mark the positions of the HiRes detectors.
Figure 5: Zenith angles of tau lepton directions for tau leptons that decay in the atmosphere.
Figure 6: The HiRes neutrino flux limits in context.