Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 5 (HE part 2), pages 1377–1380

ID 708

30TH INTERNATIONAL COSMIC RAY CONFERENCE

An upper limit on the electron-neutrino flux from the HiRes instrument

L. M. SCOTT[1] FOR THE HIGH RESOLUTION FLY'S EYE COLLABORATION
[1]*Rutgers, the State University of New Jersey, Piscataway, New Jersey, 08854, USA*
lscott@physics.rutgers.edu

Abstract: Air-fluorescence detectors such as the High Resolution Fly's Eye (HiRes) instrument are very sensitive to upward-going, Earth-skimming ultrahigh 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 is responsible for a significant decrease in the cross sections for bremsstrahlung and pair production, rendering charged-current electron-neutrino-induced showers occurring deep in the Earth's crust detectable as they exit the Earth into the atmosphere. A search for upward-going neutrino-induced showers in the entire HiRes-II monocular dataset 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. A full detector Monte Carlo simulation to determine the detector response to upward-going electron-neutrino-induced cascades is described and an upper limit on the flux of electron-neutrinos is given.

Introduction

We report on the search for upward-going electron-neutrino showers in the High Resolution Fly's Eye data set. The HiRes project has been discussed previously [1, 2]; the instrument is an air-fluorescence detector located on two sites 12.6 km apart in Utah on the U.S. Army Dugway Proving Ground. The HiRes-II detector, located on Camel's Back Ridge, is composed of 42 3.7 m^2 spherical mirrors covering nearly 360° in azimuth and between 3°-31° in elevation.

Neutrinos with energies in excess of 10^{18} eV are produced via π and μ decays following photopion production from high-energy cosmic ray protons incident on the cosmic microwave background radiation [3, 4].

Although large uncertainties exist, neutrino cross sections have been calculated to range from $\sim 10^{-32}$ cm^{-2} at 10^{18} eV to $\sim 10^{-31}$ cm^{-2} at 10^{21} eV [5, 6]. 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 only a few degrees.

Electromagnetic cascades initiated by a high-energy electron created via a charged-current electron-neutrino interaction in the earth's crust will develop much more slowly due to the onset of the Landau-Pomeranchuk-Migdal (LPM) effect. The LPM effect, first described classically in 1953 by Landau and Pomeranchuk [7] and later given a quantum-mechanical treatment by Migdal in 1956 [8], predicts that the cross sections for bremsstrahlung and pair-production should decrease for a high-energy charged particle propagating in a dense medium, effectively increasing the formation length until it is comparable to the length for multiple scattering (a detailed, more modern approach can be found in [9, 10]).

It is most probable that a neutrino-induced electromagnetic cascade would be characterized by a long, nearly-horizontal track seen in the HiRes-II ring-one mirrors, which have viewing angles between 3 and 17 degrees above the horizon. 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 energy to be detected by HiRes-II, thereby greatly increasing the aperture of the instrument at high energies.

We conducted a search for neutrinos in the entire HiRes-II data set, which extends from late 1999 to Spring 2006. No events were found to be conclusively evident of an upward-going neutrino shower.

Simulating electron-neutrino-induced electromagnetic cascades

In order to treat charged-current electron-neutrino 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 not only to know the number of charged particles at a given depth in rock, but also the energy spectrum of these particles as they leave the ground and enter the atmosphere.

Following the formalism of [11] for calculating the energy-dependence of the probabilities for undergoing pair production and bremsstrahlung at LPM energies, and taking into account any other losses (e.g. Compton scattering, ionization energy loss), we developed a routine to calculate the number of charged particles, N_e, and the energy spectrum in 1060 energy bins, at 1 g/cm^2 steps along the shower profile in rock, and for every decade in initial electron energy from 10^{12} to 10^{21} eV.

A similar calculation was performed for electromagnetic showers in air in the same energy range, however since the LPM effect begins to turn off as the density of air decreases with altitude, additional showers were generated at each energy at air densities corresponding to 1.4 km (the altitude of the desert floor in Dugway), 5, 7.5, 10, 12.5, and 15 km above sea level. We choose 16 km (an air pressure of about 0.1 atm) as the altitude above which the air-fluorescence yield effectively cuts off, yielding no fluorescence photons. The resulting observable profile in air was then found from a superposition of showers obtained from the energy spectrum in each of the 1060 energy bins at the depth to which the shower had propagated in rock.

Figure 1 shows the profiles of five electron-induced air showers emerging from the ground at different depths along a 10^{20} eV electron-induced shower in rock.

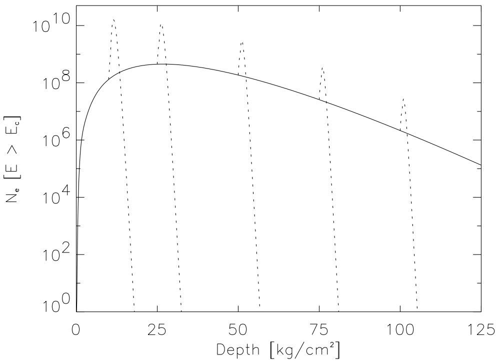

Figure 1: A 10^{20} eV electron shower profile in rock (solid line) with shower profiles for five air showers emerging from the ground at depths of 10000, 25000, 50000, 75000, and 100000 g/cm^2 (dashed lines)

The Monte Carlo

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 from 58.4 km to the surface (crust) were taken to be 4.60 and 2.80 g/cm^3 respectively. The atmosphere was allowed to extend 50 km above sea level with a density changing exponentially as a function of height.

Electron-neutrino energies were chosen at random from a flat distribution in $\log\ E$ in eV from 18 to 21. The energy-dependence of the charged- and neutral-current νN interaction cross sections were calculated based on the pQCD CTEQ5 model [12, 13]. From the ratio of the cross sections for charged- and neutral-current interactions, 70% of the events were thrown as charged-current events, while the remaining 30% were considered neutral-current events. In the case of a charged-current interaction, the most optimistic scenario was considered, where the total energy of the primary neutrino given to the secondary electron (for neutral-current interactions, the resulting hadron was given 25% of the primary energy). The shower profiles were then calculated using the LPM effect in the case of electromagnetic cascades and the standard Gaisser-Hillas model [14] in the case of hadronic cascades.

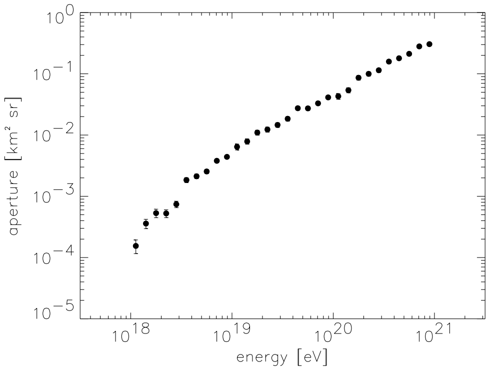

Figure 2: The HiRes-II electron-neutrino aperture.

Neutrino arrival directions were chosen at random such that they only penetrated the earth with a maximum elevation angle of 15°. Events with elevation angles greater than 15° do not contribute appreciably to the total neutrino aperture due to the tiny probability of their transmission through the crust and mantle and subsequent interaction near the instrument (a 10^{18} eV neutrino at 15° has a probability of $\sim 10^{-10}$ of transmission and interaction near the detector; this value drops to $\sim 10^{-40}$ at 10^{21} eV).

The depth, d, in the crust at which a charged- or neutral-current interaction can occur and yield at least $N_e = 10^7$ particles in air was found. The probability of transmission along the entire neutrino trajectory until point d was calculated in the normal way. The "interaction length" was then taken to be the distance along the trajectory from point d to the point where the trajectory passed 16 km above sea level. The probability of interaction was then calculated for this distance. A total detection efficiency for each event, ϵ, was calculated from the product of the transmission probability and interaction probability. For neutrinos in the smallest angular bin that do not pass through the earth, the probability of transmission was calculated from the amount of atmosphere penetrated beneath the horizon at HiRes-II; the interaction probability was calculated using the amount of material penetrated from the horizon to passage above 16 km. The neutrino was then forced to interact at a random location along the interaction length. The corresponding electromagnetic or hadronic shower profile was then created, with N_e calculated in 25-g/cm^2 steps along the shower trajectory and scaled for variations in the density of air along the trajectory, as discussed in the previous section.

Each event was then passed through the standard HiRes-II full detector Monte Carlo simulation modified for upward-going events. All showers that triggered the detector were processed employing the same routines used to time- and plane-fit, as well as filter, real data during the search for neutrinos in the upward-going HiRes-II data.

Calculating an electron-neutrino flux upper limit

We calculate the electron-neutrino aperture from the product of ϵ and the number of good events that trigger the detector. The aperture is shown in Figure 2. In order to be consistent with our current study of tau-neutrinos [15], 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.

Since we observe no neutrino events over the entire range of energy, at the 90% confidence level, we calculate a flux limit of 3.82×10^3, 3.26×10^3 and 4.25×10^3 eV cm^{-2} sr^{-1} s^{-1} at $10^{18.5}$, $10^{19.5}$ and $10^{20.5}$ eV, respectively. Combined with our tau-neutrino results and assuming equal mixing of all neutrino flavors, this reduces the limit to 3.78×10^2, 9.50×10^2 and 3.71×10^3 eV cm^{-2} sr^{-1} s^{-1}.

Conclusion

Figure 3 shows the upper limit on the neutrino flux from the analysis of the HiRes electron- and tau-neutrino flux limits as compared to two theoretical curves and to calculated flux limits from other experiments. The electron-neutrino flux limits reported here have improved upon those for the Fly's Eye by about two and a half orders of magnitude. Combined with the results of the tau-neutrino analysis, this limit lies just above the theoretical limit of [16].

As is the case with all high-energy neutrino calculations, the largest uncertainty lies in the extrapolation of νN cross sections. Different cross section models can cause the limits to vary somewhat.

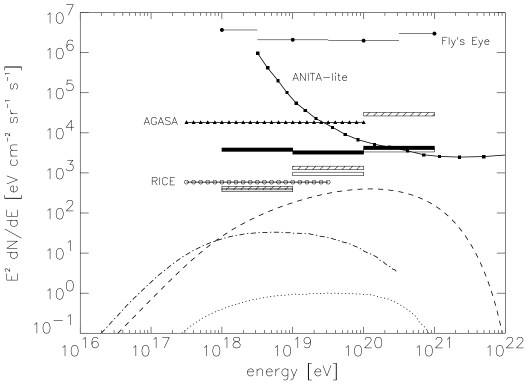

Figure 3: The HiRes-II neutrino flux-limit. *black boxes*: electron-neutrino limit (this work). *hashed boxes*: tau-neutrino limit [15] *open boxes*: electron- and tau-neutrino combined flux limit. *Dotted line*: cosmogenic electron-neutrino flux limit from fits to HiRes cosmic-ray data [18]. *Dashed line*: cosmogenic per flavor neutrino flux from fits to existing cosmic- and gamma-ray data [16]. *Dot-Dashed line*: cosmogenic per flavor neutrino flux from fits to HiRes and AGASA cosmic-ray data [19]. Also shown are calculated neutrino flux limits from the Fly's Eye [20, 21], ANITA-lite [22], RICE [23], and AGASA experiments[24].

The incorporation of cross sections from previous and more recent versions of the CTEQ model can change the limits by as much as 20 to 30%.

Recent work imposing the Froissart bound on structure functions for extrapolating νN cross sections show a decrease in cross sections at 10^{21} eV by about a factor of 8 over the CTEQ5 parameterization[17]. These cross sections would increase our electron-neutrino limit at the lowest energy bin by about 40% and increase the value of our highest energy bin by about a factor of 4.

Acknowledgments

This work was supported by US NSF grants PHY-9100221, PHY-9321949, PHY-9322298, PHY-9904048, PHY-9974537, PHY-0073057, PHY-0098826, PHY-0140688, PHY-0245428, PHY-0305516, PHY-0307098, PHY-0649681, and PHY-0703893, and by the DOE grant FG03-92ER40732. We gratefully acknowledge the contributions from the technical staffs of our home institutions. The cooperation of Colonels E. Fischer, G. Harter and G. Olsen, the US Army, and the Dugway Proving Ground staff is greatly appreciated.

References

[1] T. Abu-Zayyad, et al., 1999, *26th ICRC*, 349.
[2] J. H. Boyer et al., 2002, *Nucl. Inst. Meth.*, **A482**, 457.
[3] F. W. Stecker, 1968, *Phys. Rev. Lett.*, **21**, 101.
[4] S. H. Margolis, D. N. Schramm, and R. Silberberg, 1978, *Astrophys. J.*, **221**, 990.
[5] C. Aramo, et al. 2005, *Astropart. Phys.*, **23**, 65.
[6] M. H. Reno, 2005, *Nuc. Phys. B Proc. Suppl.*, **143**, 407.
[7] L. Landau and I. Pomeranchuk, 1953, *Dok. Akad. Nauk SSSR*, **92**, 535, 735.
[8] A. B. Migdal, 1956, *Phys. Rev.*, **103**, 1811.
[9] N. Takahashi et al., 2003, *28th ICRC*, 519.
[10] V. N. Baier and V. M. Katkov, 2004, *Phys. Lett. A*, **327**, 202.
[11] T. Stanev et al., 1982, *Phys. Rev. D.*, **25**, 1291.
[12] H. L. Lai et al., 2000, *Euro. Phys. J. C*, **12**, 375.
[13] A. Gazizov and M. Kowalski, 2005, *Comp. Phys. Comm.*, **172**, 203–213.
[14] T. K. Gaisser, 1990, *Cambridge University Press*.
[15] R. U. Abbasi, et al. 2007a, in progress.
[16] D. V. Semikoz and G. Sigl, 2004, *J. Cosm. and Astropart. Phys.*, **4**, 3.
[17] M. M. Block, 2007, *private communication*.
[18] R. U. Abbasi, et al. 2007b, in progress.
[19] D. Seckel and T. Stanev, 2005, *Phys. Rev. Lett.*, **95**, 141101.
[20] R. Baltrusaitis, et al. 1984, *Astrophys. J. Lett.*, **281**, L9.
[21] R. M. Baltrusaitis, et al. 1985, *Phys. Rev. D.*, **31**, 2192.
[22] P. W. Gorham, et al. 2004, *Phys. Rev. Lett.*, **93**, 041101.
[23] I. Kravchenko, et al., 2006, *Phys. Rev. D.*, **73(8)**, 082002.
[24] M. Chikawa et al., 2001, *27th ICRC*, **3**, 1142.