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A search for horizontal air showers induced by extremely high energy cosmic neutrinos observed by Akeno Giant Air Shower Array

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Abstract. We have made a systematic search for air shower events induced possibly by Ultra-high Energy (UHE) cosmic neutrinos by the Akeno Giant Air Shower Array. The lateral distribution of secondary shower particle densities and their shower front curvature are found to be closely related to atmospheric depth of the shower maximum which makes it possible to discriminate anomaly penetrating air shower events from the regular hadron induced air showers. The present analysis has indicated no significant enhancement on intensity of deeply penetrating air showers within the detector resolution. The resultant upper bound on UHE ν_e flux with energies greater than 3×10^{17} eV is 5.7×10^{-10} m^{-2} sec^{-1} sr^{-1} for J(E)$\sim$ E^{-2} with 95 % C.L.

1 Introduction

The attempts to detect cosmic neutrinos in UHE range *i.e.* E$\geq 10^{17}$ eV have been made by the observatories primarily for Extensive Air Showers (EAS) initiated by high energy cosmic rays. The neutrino-induced showers would be recognized by their starting deep in the atmosphere. If the detectors have sensitivity good enough to locate the shower maximum (X$_{max}$), the deeply penetrating showers (DPS) can be distinguished from the regular hadron-initiated EAS. If the ground array is able to utilizes the fact that shower front structure and particle number density distribution in EAS are closely related to longitudinal profile of EAS cascade, adequate analysis of these characteristics should lead to reasonable sensitivity on detection of deeply penetrating showers initiated by UHE neutrinos. As the Akeno Giant Air Shower Array (AGASA) (Chiba et al. , 1992) has obtained the largest exposure in UHE range, a search for anomaly deep showers by the AGASA would be able to give the lowest experimental upper bound on UHE neutrino fluxes and the presently strongest constraint on models of UHE neutrino production. In this paper we report the results of the systematic search for neutrino-induced showers with the AGASA detectors.

2 Brief Description of the Experiment

AGASA consists of 111 surface detectors deployed over an area of approximately 100 km^2 and has been in operation since 1990 (Chiba et al. , 1992). Each surface detector consists of plastic scintillators of 2.2 m^2 area and detects secondary charged particles in EAS initiated by high energy cosmic rays. The threshold energy of primary cosmic rays for reasonable reconstruction of air showers with zenith angle less than 45 degree is about 5×10^{17} eV and the detection efficiency becomes 100 % above $\sim 10^{19}$ eV, which is mainly determined by the area of the surface detector (2.2 m^2) and their separation distance ($\sim 1km$).

27 sets of proportional counters under absorbers have been

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also deployed to measure the muon component of air showers, but we do not use the signals from the muon counters in the present analysis because their detection coverage is rather limited. Contributions of muon component in EAS to signals in the surface detector is, however, taken into account since muon intensity is comparable or larger than electron intensity in horizontal air showers initiated by cosmic ray hadrons at upper layer of the atmosphere. Those events constitute backgrounds in the UHE ν search.

3 Characteristics of ν-induced EAS

Although UHE neutrinos would rarely interact with particles in air to initiate EAS, generation rate of the ν-induced EAS can be estimated by the neutrino-nucleon (νN) cross sections. In the present study, we limit our present analysis within the range of the standard particle physics and use the cross section estimated by the CTEQ parton distribution functions (Lai et al. , 1997).

The generation rate of the ν-induced EAS increases with primary energy of UHE neutrinos since the cross section gradually rises (Gandhi et al. , 1998) as $\sim E^{0.36}$ above 10^{16} eV. In the energy range the AGASA detectors measure EAS ($10^{17} \sim 10^{20}$ eV), the cross sections reach to $\geq 10^{-32}$ cm^2. The charged current reaction $\nu N \rightarrow l^{\pm} X$ dominates over the neutral current reaction and the produced lepton $l^{\pm}$ carries $\sim$ 80 % of the primary neutrino energy in average. In the present study, we consider the charged current reaction $\nu_e N \rightarrow e^{\pm} X$ for the channel to produce ν_e-induced EAS. The study on cosmic ν_μ fluxes is now under progress.

In order to seek the observable characteristics to identify ν-induced EAS, we have performed full Monte Carlo simulation using the AIRES implanted by the QGSJET hadronic interaction model with externally invoking the program of calculation of the differential cross sections of the neutrino-nucleon reactions based on the CTEQ parton distribution (Lai et al. , 1997). As UHE neutrinos can interact anywhere in air, the ground array observes variant stages of the initiated EAS cascade developments in event by event depending on atmospheric depth of their first interaction points. The simulation results indicated that this dependence would appear as the difference of lateral distribution of shower particle densities and that of curvature of the shower disc front. Lateral distribution of shower particles can be characterized by the slope parameter η in the experimentally-fitted empirical functions (Yoshida et al. , 1994; Hayashida et al. , 1995), and the shower front curvature can be characterized by the empirical formula of the delay time of the first particle arrival from the plane shower front (Hara et al. , 1979) which has a core distance dependence as $T_d \sim (1 + R/30\mathrm{m})^{\delta}$. When the induced shower is observed near its shower maximum, which corresponds to deep penetration of the cascade in atmosphere in case of horizontal directions, the lateral distribution becomes steeper (larger η) and the disc curvature becomes more prominent (larger δ). It implies that fitting of η and δ in principle can deduce X$_{max}$ and that possible DPS events can be searched by an adequate data analysis.

4 The Analysis Procedure and the Expected Sensitivity

Fitting of η and δ in actual data has strong correlation with estimation of both the shower core location and the arrival direction because determination of η and δ requires geometrical information of the observed EAS event. Especially the AGASA data analysis needs to pay careful attention to this point since the resolution of geometrical reconstruction of horizontal showers is relatively poor because the surface detector is a thin plastic scintillator with only 5 cm thickness. Our analysis procedure for deducing η and δ is consequently contained in a part of the geometrical reconstruction procedure of horizontal air showers. The detailed procedure is written in elsewhere (Yoshida et al. , 2001).

X$_{max}$ is estimated by the fitted η and δ (X$^{\eta}_{max}$ and X$^{\delta}_{max}$, respectively) using the average dependence of these parameters on the longitudinal shower profile obtained by the AIRES simulation. This approach does not fully need to rely on the zenith angle estimation, which would be a great advantage in case of the AGASA detectors where geometrical reconstruction of HAS is expected to contain larger errors. The 68 % C.L. of their resolution is ΔX$_{max} \sim \pm$1300g/cm^2. For the hadron-induced EAS, we find ΔX$_{max} \sim \pm$600g/cm^2. This level of the resolution is acceptable enough to search for UHE neutrinos since ν-induced showers could have their shower maximum well deeper than 2500g/cm^2.

In search for UHE ν's, effective reduction of HAS events initiated by cosmic ray hadrons is a key to improve the sensitivity. We applied the same analysis procedures to events of proton-induced EAS simulated by the event generator in order to find the several criteria for reduction of the hadron contamination. The following criteria were found to have the best performance to reduce hadron events and is applied in the present analysis: For all the events with zenith angle of the estimated arrival direction larger than 60 degree and with more than 6 detectors recording the signals (PASS0), we first require summation of the shower particle density in detectors recording more than 10 m^{-2} which we define as $\sum \rho_{10}$ to be beyond 50 m^{-2} and that $\chi^2_\eta \leq 10$ and $\chi^2_\delta \leq 100$ (PASS1). For events with $\sum \rho_{100} \geq 100\mathrm{m}^{-2}$ this requirement is softened to demand only $\chi^2_\delta \leq 100$. All the events with $\sum \rho_{100} \geq 1000\mathrm{m}^{-2}$ is immediately passed in this selection. Next (PASS2), the events are required that $|$ X$^{\eta}_{max}-$X$_{slant}| \leq$ 500 g/cm^2 where X$_{slant}$ is the slant atmospheric depth of the AGASA array center along the shower axis. In addition, more than two detectors must record particle density larger than 10 m^{-2} in this category. Finally (PASS3) we require X$^{\eta}_{max} \geq$ 2500 g/cm^2 and X$^{\delta}_{max} \geq$ 2500 g/cm^2.

FIG. 1 shows the expected distribution of linearly combined $X^{\eta+\delta}_{max} \equiv (X^{\eta}_{max} + X^{\delta}_{max})/\sqrt{2}$. It is clearly seen that contribution of neutrinos is larger than that of hadrons in large X$^{\eta+\delta}_{max}$ region. The Monte Carlo simulation has indicated that the "signal-to-noise ratio", fraction of ν-induced

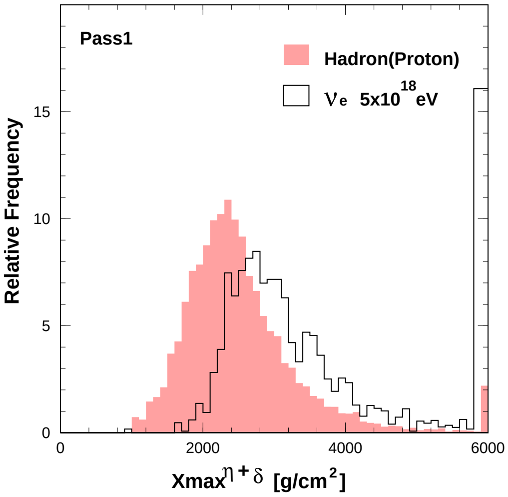

Fig. 1. The expected distribution of $X_{max}^{\eta+\delta}$ of cosmic ray hadron and neutrino events which remain after the PASS1 selection. Energies of hadrons contributed in this plot are determined by the expected energy distribution obtained by the cosmic ray energy spectrum folded with the estimated aperture for the PASS1 hadron events. Energies of the neutrinos are assumed to be 5×10^{18} eV here. Events with $X_{max}^{\eta+\delta} \geq 6000$ g/cm^2 are accumulated in the bins at the right edge.

events in the selected events, has improved by more than a decade from the PASS1 to PASS3. It should be noted, however, there is a small fraction of the hadron events remaining in the PASS3 category. They constitute the genuine background in the UHE neutrino search which cannot be discriminated by the experimental resolution. It is found that fluctuations of the density lateral distribution and the fast timing distribution, and their reconstruction errors make them look like the neutrino events. We can calculate the likelihood of the background contamination by estimation of aperture for the hadron events in the PASS3 category. The aperture of 10^{19} eV hadrons is obtained to be 0.17 km^2 sr which is less than 1 % of that for events in the PASS0 category, but certainly not negligible. The cosmic ray intensity folded with this aperture gives the expected number of background in the UHE neutrino search by the AGASA experiment.

The detection aperture for neutrinos can be calculated by folding the effective target volume with the νN cross sections. The target volume is estimated by summation of the target air depths of the simulated ν events left in the PASS3 category. We obtained $\sim$ 300 m^2 sr for ν_e's with energies of 10^{19} eV. The aperture for both neutrinos and hadrons in the PASS3 domain determines the sensitivity on a search for UHE neutrinos with the AGASA detectors.

5 Results

The AGASA data recorded from December of 1995 through November of 2000 (the effective livetime of the observation during this period is 1710.5 days) was analyzed by the same procedure described in the previous section.

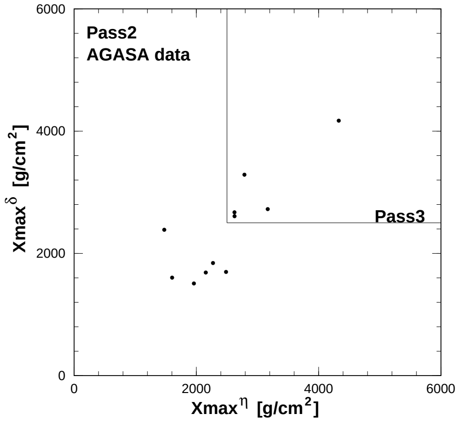

Fig. 2. The scatter plot of X_{max} deduced by the lateral distribution of shower particles (X_{max}^{η}) and by the shower front curvature (X_{max}^{δ}) for the analyzed AGASA data.

FIG. 2 is the scatter plot of the determined X_{max}. 6 events out of 12 events left after the PASS2 selection are found in the deep X_{max} region (PASS3). The event numbers in PASS2 and PASS3 should be compared with the Monte Carlo prediction of the background intensity from the cosmic ray hadron-induced showers. Since the present analysis is not able to provide the energy resolution because of inability of the longitudinal DPS profile reconstruction, the predicted background intensities have been deduced from energy integration of the differential cosmic ray energy spectrum folded with the background hadron aperture above 10^{18} eV below which there is no aperture for the hadron background. Careful attention about the accuracy of the Monte Carlo prediction must be paid here because the tail of the resolutions determines the background intensity as the remaining events in selections of PASS1 to PASS3 consists of the events in tail of the overall distribution. We carefully examined the obtained distributions of the arrival directions, $X_{max}^{\eta+\delta}$ and the other parameters in both the observed and simulated events in the PASS1 category and found fairly reasonable agreement between them. We therefore conclude that prediction of the background intensity by the method using the cosmic ray energy spectrum and the hadron background aperture is reliable enough to represent the background behavior in the neutrino-sensitive PASS3 domain.

TABLE 1 shows the expected number of events in PASS1-3 together with those observed. The uncertainties of the background prediction due to the limited accuracy of the Monte Carlo simulation we have discussed is in fact dominated by the systematic uncertainties which arises from the uncertainties of the cosmic ray energy spectrum above 10^{19} eV and of the scaling factor of primary energy to the particle densities. The systematic errors we list in TABLE 1 has accounted these uncertainties One can see that 6 events observed in the category PASS3 are consistent with the prediction, 1.72 $^{+0.14}_{-0.07}$ (stat.) $^{+0.65}_{-0.41}$ (syst.), and we found no enhancement of intensity of deeply penetrating events from the expected background. For the background including the upper errors, the 95 % C.L. upper limit of UHE ν_e integral fluxes is estimated to be 5.7×10^{-10} m^{-2}sec^{-1}sr^{-1} for $J(E) \sim$ E^{-2} and 8.8×10^{-11} m^{-2}sec^{-1}sr^{-1} for $J(E) \sim$ E^{-1} above 3×10^{17} eV where $J(E)$ is the differential energy spectrum of neutrinos.

6 Implications on the UHE neutrino models

FIG. 3 indicates the obtained limits with the several prediction of UHE neutrino fluxes. Although the proposed models are not severely constrained by the AGASA limits, several implications can be found. The AGN jet models have large uncertainties in neutrino intensity above 10^{18} eV because it highly depends on highest energies of primary protons accelerated in the jets which is quite unknown. The present limit requires the AGN neutrino spectrum to be softer than E^{-1} in EeV range if the spectrum extends beyond 10^{19} eV with the current prediction of the intensity. The scenario to explain the EHECRs observation by the collisions of UHE neutrinos with the background neutrinos (denoted as $\nu_{UHE}\nu_{2k}$ in the figure) has no ability of prediction on the neutrino spectral power index, but predicts the intensity of neutrinos at around 4×10^{21} eV. FIG. 3 shows the case when primary UHE ν spectrum follows E^{-1}. When the over density factor of the clustered background neutrino is around $f_\nu = 20$ which is the lower bound by the EGRET diffuse γ-ray observation, we find that the present AGASA limit requires the neutrino spectrum in this model to be harder than E^{-2}.

7 Summary

We have searched for signatures of UHE cosmic neutrinos in the AGASA observation. Searching for horizontal showers with steep lateral distribution of the shower particle densities and prominent curvature of the shower front disc has led to the reasonable sensitivity for ν-induced events by the ground array primarily for observing high energy cosmic rays. We found no significant enhancement of the anomalous events possibly generated by neutrinos from the expected background intensity. The obtained upper bound of neutrino fluxes put some constraints on the possible UHE neutrino spectrum in EeV range.

Table 1. Number of events observed and predicted in each category. The prediction is based on the hadron PASS3 aperture and the cosmic ray intensity with assumption that the observed comic rays contain no neutrinos. The statistical errors are due to the limited statistics of the simulated events in the hadron aperture estimation.

PASS	Observed	Predicted (No ν's)	Stat.	Syst. (Overall)
1	149	128	$^{+10}_{-1}$	$^{+31}_{-26}$
2	12	8.03	$^{+0.92}_{-0.13}$	$^{+2.31}_{-1.69}$
3	6	1.72	$^{+0.14}_{-0.07}$	$^{+0.65}_{-0.41}$

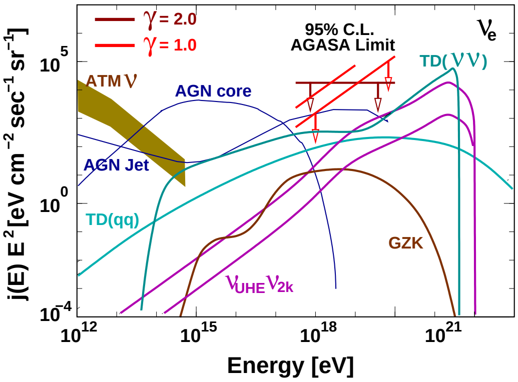

Fig. 3. The upper bound of UHE ν_e fluxes obtained by the present analysis. The power law spectrum, $J(E) \sim$ E$^{-\gamma}$, is assumed to draw the bound. The bound also depends on the highest energy of neutrinos. This dependency is shown for E^{-1} spectrum extending to 10^{19} eV and 10^{20} eV. Several predictions of the UHE neutrino models are also shown for comparison. Labels refer to $\nu_{UHE}\nu_{2k}$ (Yoshida et al , 1998), GZK (Yoshida et al. , 1997), AGN Jet (Mannheim , 1995), AGN core (Stecker and Salamon , 1996), TD (Sigl et al. , 1998).

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