Near Horizontal Showers detected with the Haverah Park Array

M. Ave, R.A. Vázquez, and E. Zas
Departamento de Física de Partículas,
Universidad de Santiago, 15706 Santiago de Compostela, Spain
J.A. Hinton and A.A. Watson
Department of Physics and Astronomy
University of Leeds, Leeds LS2 9JT ,UK

Abstract

The Haverah Park array recorded a relatively large number of inclined showers ($\theta > 60°$) which were not analysed in detail. Stimulated by the interest of the Auger collaboration in high energy neutrino detection, we are re-examining these data with a view to understanding the hadronic background against which the small neutrino flux must be detected. We describe an attempt to calculate the rate and angular distribution of the observed events. Assuming primaries are protons, the distribution of energy of the primaries which trigger the array as a function of zenith angle has been found to increase from $7\ 10^{17}$ eV at $70°$ to $3\ 10^{18}$ eV at $80°$. By selecting showers above $80°$ we show the arrival directions of relatively high energy events, some of which are from a region of sky that has been rather little studied.

1 Introduction

One of the objectives of the Auger Observatory is the analysis of very inclined showers (zenith angle $\theta > 60°$). Such analysis is of importance both to enhance the aperture of the instrument and because of interest in searching for showers produced by ultra high energy neutrinos (Capelle et al. 1998). However, analysis of inclined events is not straightforward as attenuation across the array and geomagnetic deflections of the charged particles distort the circular symmetry of the showers. To enhance our understanding of very inclined events we have begun a study of Haverah Park data obtained between 1979 and 1987 for which the initial analysis gave the zenith angle as $> 60°$. No other work on these events has been carried out, except for a study of one extremely inclined event ($\theta = 85°$) which attracted attention because densities were recorded in 20 detectors (Andrews et al. 1969, Hillas et al. 1969). This event, produced by a primary of energy above 5×10^{19} eV, served mainly to highlight the complexity of the analysis needed. Now, with improved computing power, after significant developments in shower modeling and with the motivation of the superior data anticipated from the Auger Observatory, we have started to learn how to deal with such events: our first steps in this process are reported here.

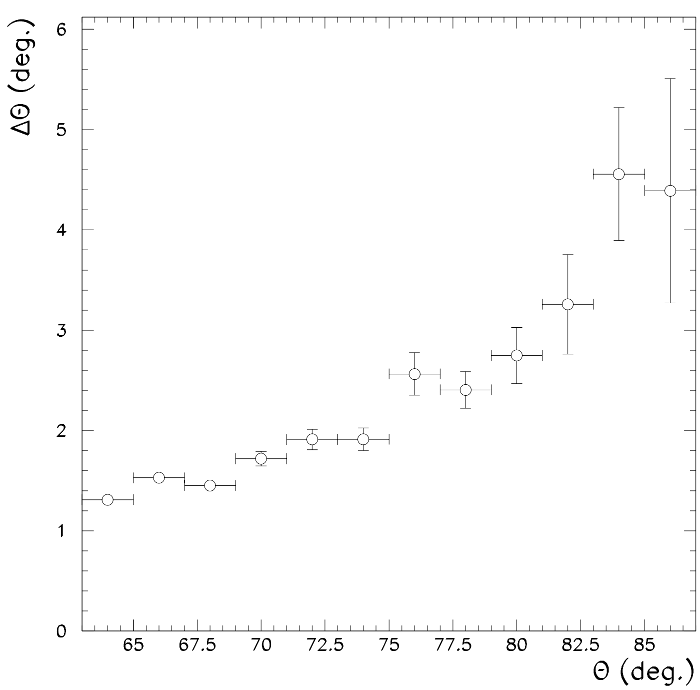

Figure 1: Zenith angle uncertainty as a function of zenith angle for inclined showers measured in the Haverah Park array.

2 Rate Comparison

The arrival direction of events initially calculated to be above 60° have been reanalysed assuming a plane front for the muons and using all available timing information. Previously only times from the four central triggering detectors were used to compute the arrival directions of these events (Lawrence, Reid, and Watson 1991). The uncertainty in the arrival direction for each event has been significantly reduced. Fig. 1 shows the average uncertainty in zenith angle of the reconstructed events as a function of zenith. The uncertainty in azimuth is approximately constant at $\approx 1^\circ$.

The interpretation of the data for angles above 60° requires a good understanding of the properties of inclined air showers initiated by hadrons. We have simulated showers of different zenith angles using AIRES (Sciutto, 1998) taking proper account of the magnetic field strength and direction at Haverah Park. As the zenith angle increases the depth of atmosphere rises, doubling the vertical value at 60° and becoming over six times larger at 80°.
In such inclined showers an increasing fraction of the electromagnetic component is absorbed before reaching the ground and can be neglected above 70°. Muons survive provided their energy is high enough to travel the distance between production in the top layers of the atmosphere and the observation level. As this distance grows with increasing zenith angle, the muon energy rises proportionally and at 80° the average is over 100 GeV in the central 3 km^2 of the shower. For this reason muons arrive in a very flat plane (Billoir et al. 1997). The Earth's magnetic field acts over these long distances to bend the muon trajectories, separating positive and negative particles so that the density distributions on the ground have rather complex structures which are far from circularly symmetric. For angles above 80° the structures exhibit complex double lobes as first pointed out by Hillas et al. (1969).

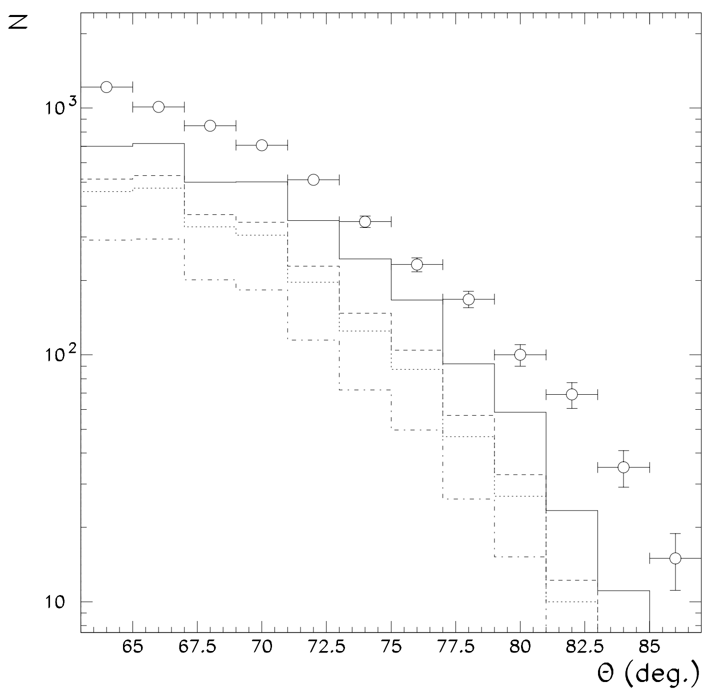

Figure 2: Simulated rate as a function of zenith angle compared to data. Broken curves illustrate the effects of different contributions to the rate. The bottom line is the contribution due to muon track length only and curves going upwards show the effect of adding δ-rays, pair production and bremsstrahlung, and direct light on the PMTs. Proton primaries are assumed.

We have made a Monte Carlo simulation of the detector to compare the observed event rate with expectation. Because of the complex density pattern at the detection level, simplifying methods were used to reduce the massive amount of computing time which would be required for a complete simulation. Showers of different energies are generated by rescaling the density contour maps for the muons. The average muon density has been checked to be proportional to $E^{0.85}$ to an accuracy of about 10%. Full details will be given in Ave (2000) and a more detailed paper.

The program uses a sample of proton primary showers at different zenith angles and a fixed energy of 10^{19} eV from which average densities are obtained for different zenith and azimuthal angles. All other showers are generated with an primary energy distribution following the cosmic ray spectrum as parameterised in (Cronin 1997) and an isotropic arrival direction distribution. The particle density on the ground is tabulated and the shower is randomly positioned within an appropriate square surface surrounding the array (in some cases this is as large as 60×60 km^2), to establish the probability of detection as a function of energy. To define the number of muons going through a detector the average number of muons is obtained from the value tabulated in the corresponding bin making use of energy scaling. The number of muons is assumed to follow a Poissonian distribution.

We have studied the light distribution in the tanks using a modified version of WTANK (de Mello Neto, 1998) based on GEANT (Computing and Network Division CERN,1994) and originally designed for the Auger Observatory. The output signal reflects the total muon track length, fixed by the tank geometry, but it is supplemented by contributions from direct light onto the photocathodes of the photomultipliers, δ-ray production, pair production and bremsstrahlung. These contributions, listed in decreasing order of importance, mean that the light output from a single muon is asymmetrically distributed about the most probable value with a tail extending to high photoelectron numbers. In the simulation, the tank response to the muons has been modelled taking into account the above factors which are very important for the triggering of inclined showers.

Figure 2 displays the recorded shower rate rate as a function of zenith angle, as obtained after the reanalysis of arrival directions, compared to the results of the simulation. Account has been taken of the uncertainty in the zenith angle reconstruction in the simulation. No normalisation has been made. We consider that the agreement obtained so far is encouraging and shows that we have a reasonable understanding of the triggering of the array by inclined showers. The discrepancies that remain may be removed when one or a combination of remaining uncertainties in the inputs to the simulation are added. These include the cosmic ray spectrum and composition and uncertainties associated with shower fluctuations, density averaging algorithms, the ground beneath the detectors and the approximate generation of showers in the required energy and azimuth ranges. Heavier primaries generate showers with larger mean muon densities at the ground. The inclusion of a fraction of iron nuclei in our simulations is therefore expected to increase the predicted rate.

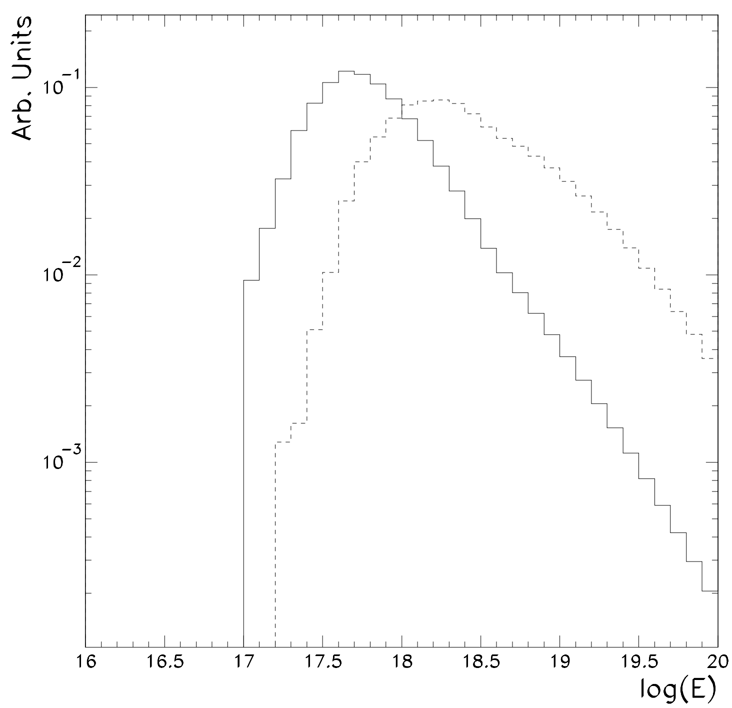

Figure 3: Energy response of the Haverah Park array to inclined showers for zenith angle 70° (continuous line) and 80° (dashed line).

Our calculation of the triggering probabilities allows energy response curves for the array to be obtained as a function of zenith angle. These curves have well-defined peaks at energies that increase with zenith angle. Examples are shown in fig. 3 for 70° and 80°. A cut on number of detectors struck is likely to narrow these distributions significantly; this is currently under investigation. Calculation of the equivalent curves for iron primaries is underway.

From figure 2 it is apparent that direct light on the photomultipliers is an important effect for high zenith angle showers. This effect complicates analysis of the Haverah Park data. The Auger observatory will have several advantages in the identification of direct light signals, due to the presence of three independent signals and detailed timing information. In addition we note that the direct light contribution will reduce the triggering threshold for neutrino primaries (and for hadron initiated showers) at large angles, thus enhancing the prospects for detection of ultra high energy neutrinos (Capelle et al. 1998).

3 Arrival Directions

We have calculated the arrival directions of the showers detected with zenith angles between 80° and 86°, totalling 160 events. The upper angle cut has been made to exclude those events that have large uncertainties in the zenith angle reconstruction. These events are shown on Fig. 4 illustrating how these events cover a part of the sky ($-30^\circ < \delta < 0^\circ$) that has been little studied. Assuming that the showers observed are induced by protons our energy response curves imply that the average energy for these events is $3\ 10^{18}$ eV and that over 67% of these showers are above 10^{18} eV. This figure has uniform exposure in RA but not, of course, in declination.

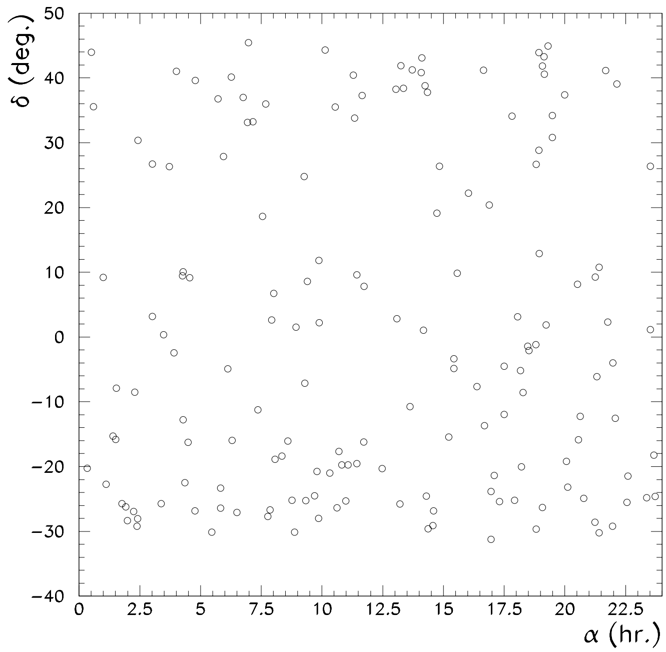

Figure 4: Right Ascension and declination of events with zenith angle greater than 80°.

4 Conclusions

We have demonstrated considerable progress in our understanding of the response of a water-Cerenkov shower array to very inclined showers. We believe that this experience can be transferred with profit to the analysis of showers from the Auger Observatory and note that even the planned engineering array will have nearly five times the collecting area of Haverah Park. In the short term it may be that a full understanding of the trigger rate as a function of zenith angle can give information on the primary cosmic ray mass composition.

References

Andrews, D. *et al.*, Proc. of the 11th ICRC, Budapest (1969), Acta Physica Academiae Scientiarum Hungaricae 29, Suppl. 3, pp. 337-342, (1970)

Ave, M. *PhD Thesis, in preparation* (2000)

Billoir, P., Bertou, X. and Pradier T., GAP note 1997-058 Analysis of Quasi-horizontal Showers Detected in the Auger Ground Detector

Capelle, J., Cronin, J.W., Parente, G., and Zas, E., *Astropart. Phys.* **8** (1998) 321.

Cronin, J., GAP note 1997-034 Analysis of the experimental spectra of the highest energy cosmic rays (1997).

Hillas, A.M. *et al.*, Proc. of the 11th ICRC, Budapest (1969), Acta Physica Academiae Scientiarum Hungaricae 29, Suppl. 3, pp. 533-538, (1970)

Lawrence, M.A., Reid, R.J.O., and Watson, A.A. 1991

GEANT Detector Description and Simulation Tool, Application Software Group, Computer and Networks Division, CERN, Geneva 1994

de Mello Neto, J.R.T., WTANK: A GEANT Surface Array Simulation Program GAP note 1998-020

Sciutto, J. AIRES: A System for Air Shower Simulation, GAP note 1998-005