STUDIES OF AIR SHOWERS PRODUCED BY PRIMARIES $> 10^{16}$ eV USING A COMBINED SCINTILLATION AND WATER-CERENKOV ARRAY

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ABSTRACT

An array of $8 \times 1.0 \, m^2$ plastic scintillation counters and 13 water-Cerenkov detectors (1 to $13.5 \, m^2$) has been operated at the centre of the Haverah Park array to study some features of air showers produced by 10^{16} eV primaries. Measurements of the scintillator lateral distribution function, the water-Cerenkov lateral distribution function and of the distance dependence of the Cerenkov/scintillator ratio are described.

1. Introduction. An array of $8 \times 1.0 \, m^2$ scintillation detectors and 13 water-Cerenkov detectors were operated at the centre of the Haverah Park array from September 1982 - December 1983. The arrangement of the array is described in Brooke et al (1983). The output from each detector is digitized locally and transmitted to a central controlling computer (Astley et al 1983). This configuration of detectors has given us the opportunity to make a number of measurements in showers with primary energy $10^{16} - 10^{17}$ eV. In addition a sample of showers with very precise core locations have been obtained for use in searches for muon-poor showers.

2. The scintillator lateral distribution function for $E > 10^{16}$ eV. In a three month period from October 1983 1531 events were recorded with $\theta < 50^{\circ}$ and with mean energy 3.5×10^{16} eV. The trigger for this run was supplied by a three-fold coincidence between $4 \times 9 \, m^2$ water-Cerenkov detectors spaced at 150 m. The scintillator lateral distribution function (LDF) was measured with the 8 scintillators using shower cores derived from water-Cerenkov data fitted to the average water-Cerenkov LDF obtained by Coy (1984). Various trial scintillator LDFs were fitted to the data (Perrett 1985). The best fit was obtained using the modified NKG lateral distribution adopted by the Akeno group (Hara et al 1979), namely

$$S(r) = \frac{NC}{r_o^2} \left[\frac{r}{r_o}\right]^{(s-2)} \left[1 + \frac{r}{r_o}\right]^{(s-4.5)} \left[1 + 0.2 \left[\frac{r}{r_o}\right]^{1.6}\right],$$

where $S(r)$ is the scintillator density at a distance r, $s = 1.07 \pm 0.01$, $r_o = 79 \, m$, $\log(NC/r_o^2) = 2.02$ and $C = 1/\{B(s, 4.5-s) + 0.2 \, B(s+1.6, 4.5-1.6-2s)\}$ where $B(z,w)$ is the beta function. The data and fit are shown in Figure 1 which is based on 108 showers with $\theta < 30^{\circ}$. Figure 2(a) and (b) show the measured variation of s with primary energy and zenith angle for a larger data set of 1531 showers with $\theta < 50^{\circ}$. The zenith angle variation of s in the range $1.0 < \sec\theta < 1.2$ was found to be $(5.1 \pm 0.6) \times 10^{-4} \, g^{-1} \, cm^2$. This value of $ds/d\sec\theta$ accounts for the different values of S, 1.07 and 1.02, measured at Haverah Park and Akeno respectively.

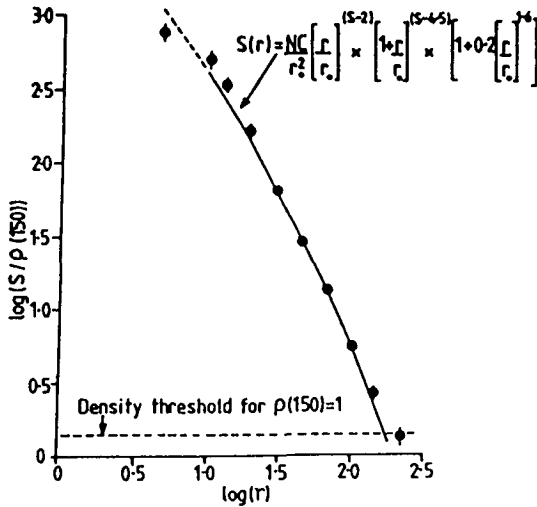3. The water-Cerenkov lateral distribution for $E > 10^{16}$ eV. Using the

Figure 1: The modified NKG LDF fitted to 108 events with $\theta < 30^\circ$. Core location was provided by the water-Cerenkov detectors. A value of 1.07 ± 0.01 was obtained for the age parameter s.
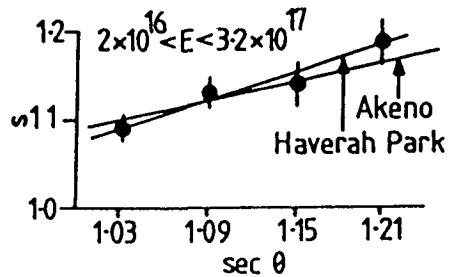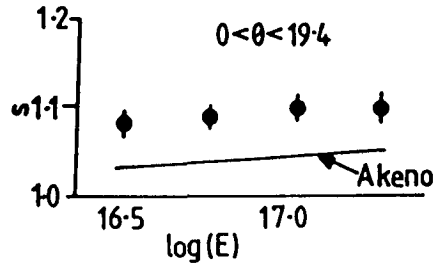
Figure 2a: The variation of s as a function of energy in the theta range $0^\circ < \theta < 19.4^\circ$.

Figure 2b: The variation of s as a function of $\sec\theta$ in the energy range $2 \times 10^{16} < E < 3.2 \times 10^{17}$. A value of $(5.1 \pm 0.6) \times 10^{-4}\ g^{-1}\ cm^2$ was obtained.

same 1531 events discussed above the water-Cerenkov LDF (described by $\rho(r) = k\ r^{-(\eta + r/4000)}$) was investigated above 10^{16} eV with the scintillator data being used to locate the shower core. These data are shown for $\theta < 30^\circ$ in Figure 3. The LDF is found to be a good fit to the data in the distance range $20 < r < 300\ m$. It is quite remarkable that this form of function (with an energy and θ-dependent η) fits water-Cerenkov data from $10^{16} - 10^{20}$ eV. To measure the variation of η with energy and zenith angle a subset of 924 events which satisfied a strict acceptance criteria (Perrett 1985) was used. A multi-parameter weighted least squares fit was carried out on the values of η derived in individual showers in the energy range $2 \times 10^{16} < E < 2 \times 10^{17}$ eV and compared with that found by Coy (1984) for $E > 2 \times 10^{17}$ eV. The results are:-

$$2 \times 10^{16} < E < 2 \times 10^{17}\ eV:\ \eta = (2.261 \pm 0.018) - (1.146 \pm 0.092)\ (\sec\theta - 1)$$
$$+ (0.192 \pm 0.035)\ \log(E/10^{17}),\ and$$

$$for\ E > 10^{17}\ eV:\qquad \eta = (2.198 \pm 0.014) - (1.275 \pm 0.051)\ (\sec\theta - 1)$$
$$+ (0.160 \pm 0.022)\ \log(E/10^{17}).$$

At $\theta = 0^\circ$, $E = 10^{17}$ eV the values of η determined in the two independent

experiments differ by 0.063 ± 0.023. We consider this good agreement in
view of the well-known difficulty of avoiding systematic errors in this
type of work. The regression coefficients have been used to calculate
the elongation rate (Linsley 1977) in each energy range. The derived
values are (99 ± 20) gcm^{-2}/decade for $10^{16} < E < 10^{17}$ eV and
(81 ± 12) gcm^{-2}/decade above 10^{17} eV. There is no evidence for any change
of elongation rate with energy from 10^{16} to 3×10^{18} eV (the effective
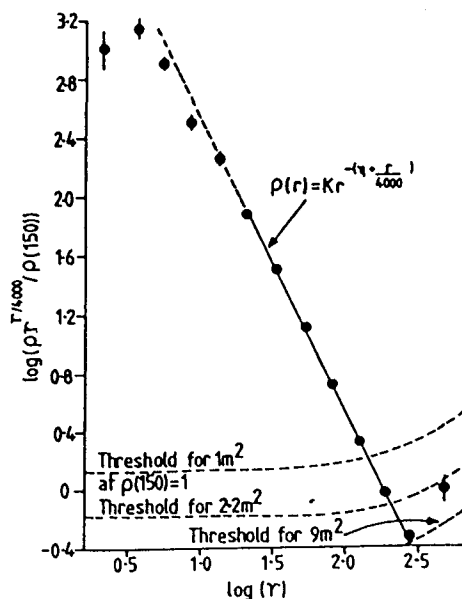upper range of the data obtained by Coy (1984)).

Figure 3: The water-Cerenkov data fitted to the Cerenkov LDF for $\theta < 30°$.
Core location was provided by the scintillation detectors.

Fluctuations between the values of η found for individual showers are
considerably larger than can be accounted for by measurement error alone.

4. The Cerenkov/Scintillator density ratio. The ratio of the density
measured in the water-Cerenkov detectors (C) to that observed in the
scintillator detectors (S) (both in units of vertical equivalent muons)
is a function of the energy of the primary initiating the shower and of
the distance of the detectors from the shower core. It is a useful
quantity both for comparison with model calculations and for use in cross-
calibration checks between arrays. In the present experiment the ratio
C/S has been measured directly for showers in the distance range
$10 < r < 200$ m for showers of mean energy 5×10^{16} eV. The data shown in
Figure 4 are for a mean zenith angle 19°. The expected rise of the C/S
ratio at small core distance is observed.

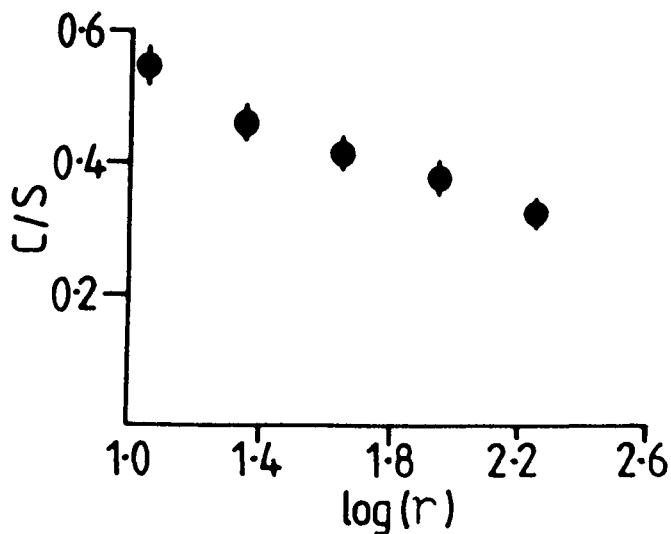Figure 4: The variation of the Cerenkov (C) to Scintillator (S) ratio as a function of   for $\theta < 19^{\circ}$ and $\bar{E} = 3.5 \times 10^{16}$ eV.

References

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