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Photomultiplier noise associated with cosmic rays

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Abstract. The effects of cosmic rays traversing photomultipliers from known directions have been observed and compared with an approximate theoretical treatment of the problem. The efficiency of a simple anti-coincidence technique for excluding such events has been measured. When night sky Čerenkov radiation produced by extensive air showers is being investigated the anti-coincidence technique cannot be used, therefore atmospheric and locally produced Čerenkov signals have been compared as a function of distance from the air shower core for two types of photomultiplier.

1. Introduction

Whilst using mechanically collimated photomultipliers to observe night sky Čerenkov radiation produced by extensive air showers we have occasionally recorded large pulses which, under our observing conditions could not be due to atmospheric Čerenkov radiation. For example, such pulses were still observed when a photomultiplier was operated with an opaque cover. Under these conditions, and in coincidence with showers of mean energy about 4×10^{15} eV centred typically 30 m from the photomultiplier, observable pulses were present on about 60% of our records. We attribute these pulses to the local production of Čerenkov light in the glass envelope of the photomultiplier by cosmic ray particles.

Young (1966) has presented pulse height spectra of a component of photomultiplier noise which is compatible with the explanation above, but was able to describe only gross features of the effect since he had no detailed knowledge of the arrival directions of the particles involved. Since the nature of some experiments, such as those involving air showers, prevents the use of anti-coincidence techniques to remove this noise component, it is of some importance to understand in more detail the properties of signals induced in photomultipliers by sea level cosmic rays. We have studied the effects of cosmic rays impinging on photomultipliers from known directions and compared these observations with the results of an approximate theoretical treatment.

2. Theory

We have calculated the number of Čerenkov photons produced in the photomultiplier face and falling on the photocathode for various directions of the incident particle on the assumption of an infinite photocathode. This approximation has the virtue of comparative simplicity and illuminates the main features of the interaction.

The geometry assumed is shown in figure 1. A particle enters the tube face at an angle α to the inward normal and emits photons at the Čerenkov angle θ_C to its track for as long as its velocity in the glass is greater than a threshold given by

$$v_T = c/n$$

(c is the velocity of light in vacuum and n is the refractive index of the glass). In our case

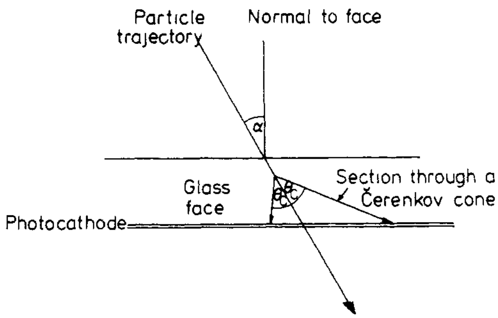

Figure 1. Particle trajectory and a section through the Čerenkov cone in a glass phototube face.

n is close to 1·5 corresponding to kinetic energy thresholds of 170 keV and 36 MeV for electrons and muons respectively. Photon yields rise quite slowly with kinetic energy reaching 90% of the asymptotic high energy value at kinetic energies of about 1 MeV and 200 MeV respectively. These energies are commonplace for sea level cosmic rays (Hayakawa 1969) so photon yields close to the asymptotic value (Jelley 1958) of

$$\frac{2\pi}{137}\sin^2\theta_C \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^2} \text{ photons (unit length)}^{-1}$$

can be assumed with some confidence ($\lambda_2 - \lambda_1$ is the range of observed wavelengths). A single cosmic ray particle incident normally on the 1 cm thick face of our photomultiplier (EMI 9623B with S11 photocathode) would give rise to about 80 photoelectrons. In this calculation we have ignored the possible change of quantum efficiency of the photocathode with angle of incidence and the possibility of successive internal reflections in the glass.

We have further calculated the expected number of photoelectrons produced by single relativistic particles incident at angles spaced by 10° from 0° to 180° to the inwardly directed normal. The Čerenkov light may interact with the photocathode either directly or after internal reflection by the glass–air interface at the front of the tube face. The calculation does not include allowance for radiation from other regions of the glass envelope although this is not necessarily negligible in fact. Calculations were made for single photons at 10° intervals around the azimuth of the Čerenkov cone, hence the curves exhibit some quantization effects which are artifacts of the calculation procedure. These depend on how many of a limited number of test photons are actually observed. Čerenkov light is radially polarized and the reflection coefficients are not obvious. They may be calculated in a relatively straightforward application of classical formulae as indicated in the appendix. Figure 2 (open circles) shows the results of the calculations and gives the relative numbers of photons per unit track length which impinge on the photocathode, either directly or after a single front-face reflection. No

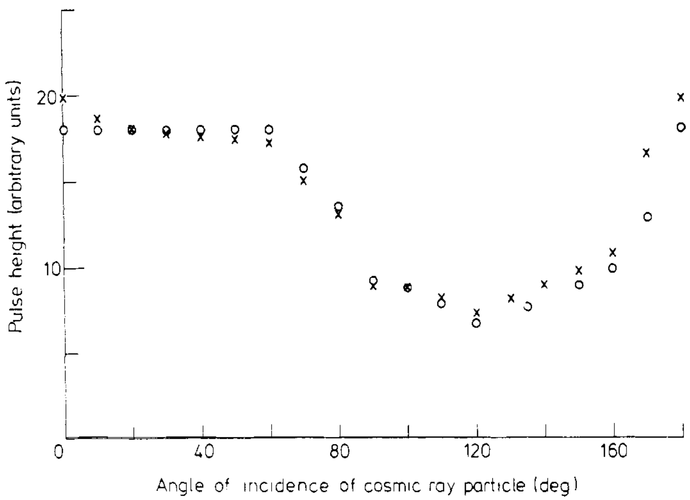

Figure 2. Calculated dependence of the observed number of Čerenkov photons per unit particle track length on the angle of incidence of the particle. ○, no reflection by the photocathode; ×, 25% of photons incident on the photocathode specularly reflected (normalized to ○ at 20°).

edge effects are included since an infinite photocathode is assumed. If no photons are reflected back from the photocathode figure 2 predicts the angular distribution of mean photomultiplier pulse height per unit track length. The main features of this distribution are a broad maximum for particles incident near normal from the front of the face, a minimum at about 120° and a sharp peak close to 180° when the particles approach the photocathode from behind. The critical angle for the glass–air interface is 42° so when a particle is incident at 180° the Čerenkov angle of 48° is sufficient to ensure complete reflection of all photons back to the photocathode. At angles of incidence less than 174° the reflection is no longer complete resulting in reduced signals.

We have examined the theoretical case where unabsorbed photons are specularly reflected at the photocathode and return to it after further reflection at the front face of the tube. The angular dependence indicated by crosses in figure 2 was derived for this case with the assumption that 25% of incident photons emitted from particles at 0° incidence return to the photocathode. The curves in figure 2 are arbitrarily normalized at 20° to emphasize the fact that there is no gross change in the shape of the curves. In absolute terms the data which include reflection would be 25% higher at 0°. Our data (see later) suggest that this may be of the right order of magnitude.

Single particles passing through the tube face will have a track length proportional to $\sec\alpha$ in an infinite face. Inclusion of this $\sec\alpha$ dependence results in an infinite maximum at 90°, but the effective tube area exposed to such particles is reduced by the same $\sec\alpha$ factor and the number of such pulses should be reduced proportionately. One might expect therefore that the mean pulse height per particle should approximate to the angular dependence of figure 3 while the time average of the pulse heights should be as shown in figure 2.

We have also calculated the equivalent of figure 2 for a tube whose face has an optically black front surface. The result, shown in figure 4, shows the importance of reflections from the front face and provides a valuable point of comparison with our experiments.

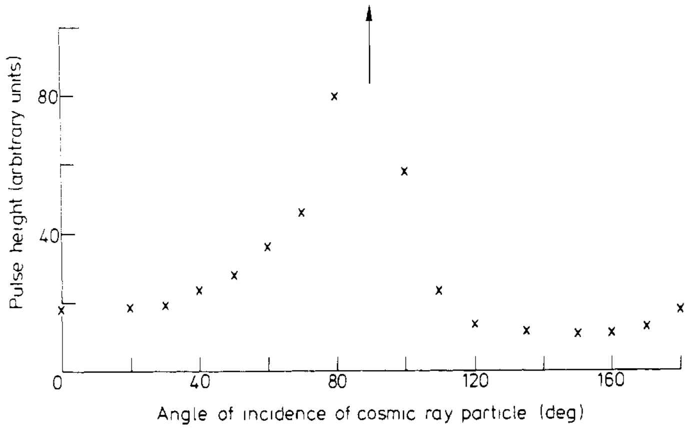

Figure 3. Calculated angular dependence of the detected Čerenkov photons (assuming no photocathode reflection) per incident particle.

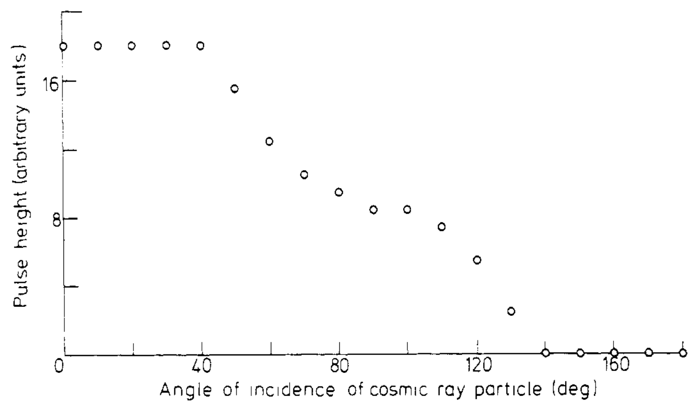

Figure 4. Calculated angular dependence of the detected Čerenkov photons per unit track length with a blackened tube front face.

3. Experimental

The main series of experiments was carried out with an EMI 9623B photomultiplier having a 1 cm thick by 17·5 cm diameter glass face of refractive index close to 1·5. Cosmic ray particles were selected by a 'telescope' consisting of two more EMI 9623B tubes optically coupled to disks of plastic scintillator and operated with a coincidence rate of a few per minute. The plastic scintillators were separated vertically by 135 cm thus defining a beam of cosmic rays with a diameter of 17·5 cm and an angular spread of $7\frac{1}{2}°$ (half angle). The third photomultiplier was placed within this beam at the required orientation and the pulse height spectrum accumulated for some hours on a 1024 channel multi-channel analyser gated with the coincidence signal. Checks were made on the photocathode uniformity and on the variation of tube gain with orientation. In the former case a green pulsed light emitting diode (λ = 565 nm) was shone through a small hole to illuminate small areas of photocathode and the observed pulse height noted for a large number of illuminated regions. The spectrum of pulse heights obtained for a fixed source luminosity is shown in figure 5. Čerenkov photons produced by particles passing through a photomultiplier faceplate are likely to be localized in their interaction with the photocathode and hence this distribution will play a significant role in broadening the spectra shown in figure 6. The variation of tube gain with orientation was checked carefully and found to be less than 4%. Care was taken to cover thoroughly the anomalous angular regions discussed below. Some typical spectra

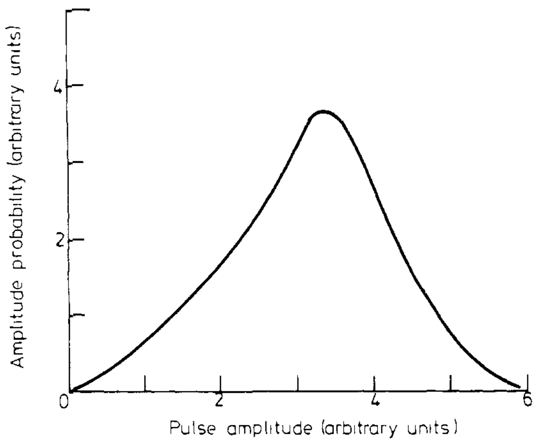

Figure 5. Statistical distribution of photocathode sensitivity for the EMI 9623B photomultiplier over the whole of the exposed front face.

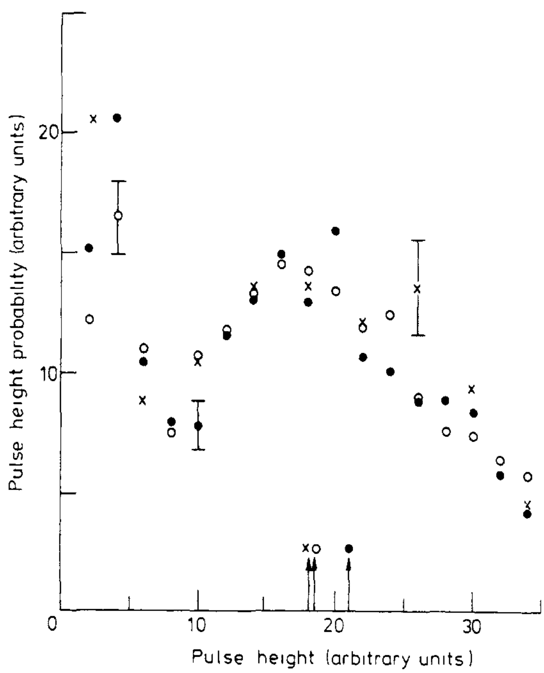

Figure 6. Pulse height spectra of observed glass Čerenkov pulses. Particle angles of incidence: ●, clear face, 0°; ○, clear face, 180°; ×, 0° with blackened face. Mean pulse heights indicated.

of cosmic ray induced pulses are shown in figures 6 and 7. Comparison of the results of figure 6 shows that removing the effect of reflection makes little (about 15%) difference to mean pulse height under these conditions and at small angles of incidence, whereas figures 6 and 7 demonstrate clearly the effect of the black paint in reducing signals from an inverted tube. However, figure 7 also shows the existence of a residual effect of cosmic rays on the blackened tube as compared with a background (ungated) spectrum. This may be due to imperfect blackening of the face, scintillations in the glass, Čerenkov or scintillation light produced in the rest of the envelope or to direct particle stimulated emission from the dynodes or photocathode.

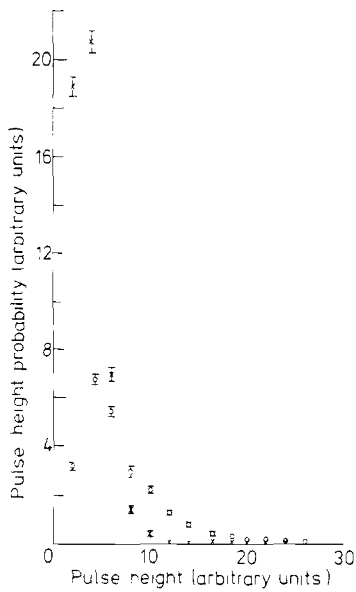

Figure 7. Pulse height spectra of EMI 9623B phototube noise (×) and of glass Čerenkov pulses for particles incident at 180° on to a blackened tube face (○).

After the subtraction of noise, spectra such as figure 6 were used to find mean pulse heights at various angles. The means for the curves in figure 6 are indicated therein. The results are plotted in figures 8 and 9 together with schematic representations of the theoretical data of figures 2 and 4. The curves are normalized at small angles of incidence where total internal reflections at the edge of the photomultiplier face should minimize edge corrections.

We were interested to discover the extent to which internal reflection (Gunter *et al* 1970) of the Čerenkov light within the photomultiplier face contributed to the effects discussed above. For this purpose, a scaled down telescope was constructed with the same angular response as before but employing scintillators with only 5 cm diameter. The EMI 9623 tube was then placed so that the cosmic ray beam passed through the centre of the upward viewing face. This would reduce the effect of internally reflected light being lost at the edge of the face. A comparison was made again between the tube with a clear face and the blackened face at 0°. The blackened face exhibited a reduction of 21% in the amplitude of the peak of the observed pulse height spectrum, corresponding to a reflected flux of 27% of the incident flux on the photocathode

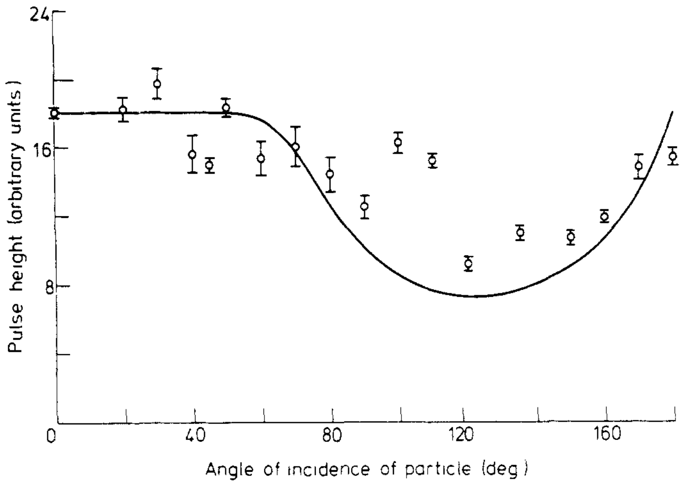

Figure 8. Observed angular dependence of the mean amplitude of cosmic ray induced photomultiplier noise pulses. A schematic of figure 2 is indicated.

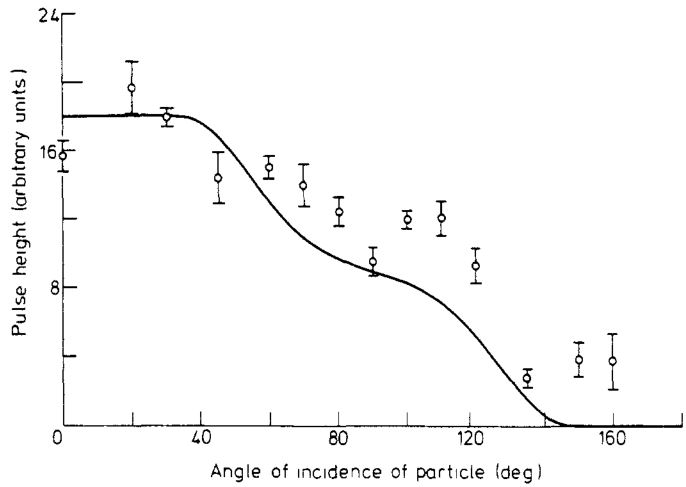

Figure 9. Observed angular dependence of the mean amplitude of cosmic ray induced photomultiplier noise pulses for a blackened tube face. A schematic of figure 4 is indicated.

assuming specular reflection at the photocathode. A smaller (7·5 cm) RCA 8054 tube was examined in a similar way. The S11 photocathode of this tube gave a reflected flux of 22% of that incident. A Čerenkov pulse height spectrum for this tube is shown in figure 11.

4. Discussion

There is general qualitative agreement between theory and experiment both with clear and blackened faces but in each case there are two angular regions which may be anomalous, namely around 40° and 105°. It seems possible that these are due to inadequacy of the theoretical treatment, for example at 40° angle of incidence of the particle some of the Čerenkov light will travel nearly parallel to the photocathode and be lost through the edge of the face. No such simple explanation is apparent for the effect at 105°.

The effect of reflection from the clear front face is shown in figure 10 where we have plotted the difference between figures 8 and 9. The anomaly at 105° is largely suppressed while the theoretical feature at about 70° due to the onset of reflection from the front of the clear tube is not present, possibly due to losses through the edge of the face. Agreement at 0° and 180° is good, particularly when the finite resolution of the counter telescope is taken into account and the peak at 180° is seen to be not fully resolved.

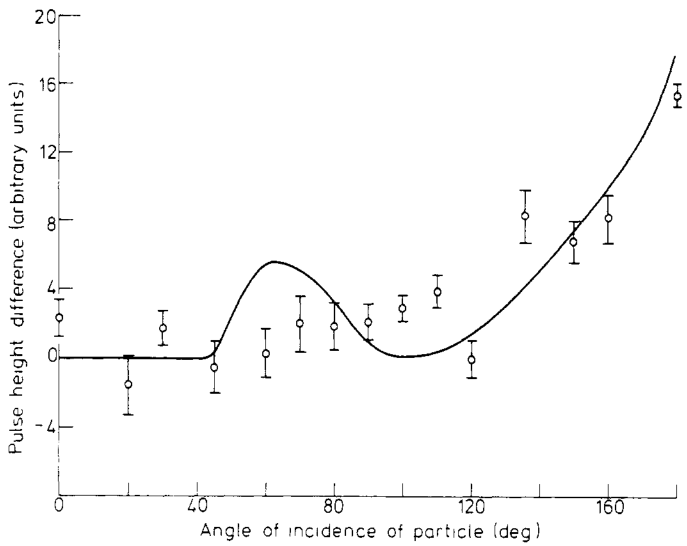

Figure 10. Observed difference between mean observed pulse heights for a tube with clear and blackened face. A schematic of the difference between figures 2 and 4 is indicated.

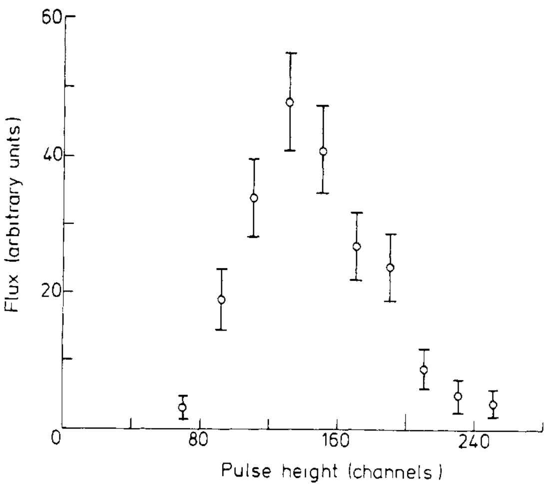

Figure 11. Pulse height spectrum of cosmic ray induced noise in RCA 8054 photomultiplier (angle of incidence = 0°).

There are at least two unknowns which could contribute to anomalies in the distributions. Firstly, Čerenkov light may be produced in regions of the tube envelope other than the face. This light might channel within the glass to the face or travel through the tube to the photocathode for favourable particle directions. With either mechanism, relatively sharp angular features might occur. Secondly, we have no information on the absorption of the glass–black paint interface when viewed from the glass. This could also have an angular dependence.

In order to remove noise from our spectra, we subtracted a distribution such as figure 7 (open circles). It is clearly insufficient to compare merely ungated tube noise to effects which are observed when a cosmic ray particle is present. Thus, the case chosen was that in which no signal is expected but a particle is present. That is the 180° case when all Čerenkov light produced in the face should be absorbed but scintillations in the face and envelope and Čerenkov light from the envelope may still be present. The magnitude of this residual component will change with angle so, at best, this subtraction technique is only a better approximation. The 105° anomaly may also be due to an angular dependent residual effect since an excess is observed both when the tube is clear and blackened.

5. Practical applications

It is clear from the discussion above that glass Čerenkov light can be a major noise source for photomultipliers used in cosmic ray work. The flux of sea level cosmic rays is roughly 1 cm^{-2} min^{-1} through a horizontal surface and it is of interest to discover how great a contribution this component makes to the *total* large amplitude noise in the photomultipliers tested. We placed the RCA 8054 tube immediately below a 17·5 cm diameter photomultiplier and scintillator, the pulses from which were used as an anti-coincidence gate for noise pulses from the tube under test which was itself shielded from the scintillation light. Figure 13 shows a comparison between the tube noise, first ungated and then gated in anti-coincidence with the local energetic particle flux. A considerable reduction in noise is apparent for the larger noise pulses and the total number of pulses removed corresponds to $0{\cdot}97 \pm 0{\cdot}05$ cm^{-2} min^{-1}, rather close to the value mentioned above. The same effect has been observed for the EMI 9623 tube but with a scintillator of comparable dimensions to the photocathode. The efficiency of gating out cosmic ray effects was reduced but a significant noise reduction was still achieved.

Our interest in the glass Čerenkov noise problem began with our work with atmospheric Čerenkov radiation associated with cosmic ray showers. Figure 13 shows a comparison between the number of atmospheric Čerenkov photons incident on the photocathode of our EMI 9623B at various distances from the core of a 10^6 particle shower (after Protheroe *et al* 1975) and the number of photons due to glass Čerenkov radiation by the local shower particles. In the latter case the curve is actually the product of the number density of particles (Greisen 1960) and the number of Čerenkov photons per particle. Allowance has been made for the absorption of photons between their point of production and the photocathode but no correction is included for reflection losses at the front surface of the tube as this depends on the angle of incidence of the Čerenkov photons. Approximately 50% of externally produced Čerenkov photons in the wavelength range 300 nm to 600 nm are absorbed in the glass face of a 9623B tube.

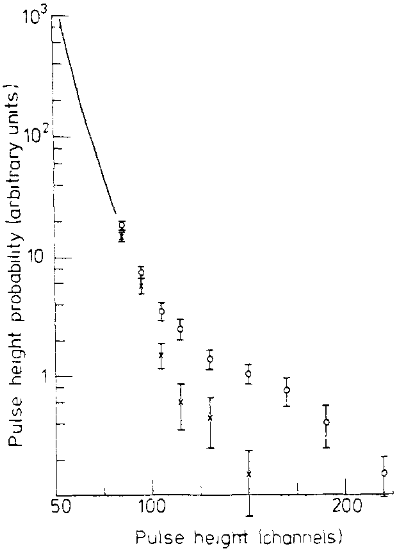

Figure 12. Noise pulse height spectra for RCA 8054 tube: ○, ungated; ×, gated in anti-coincidence with cosmic ray particles.

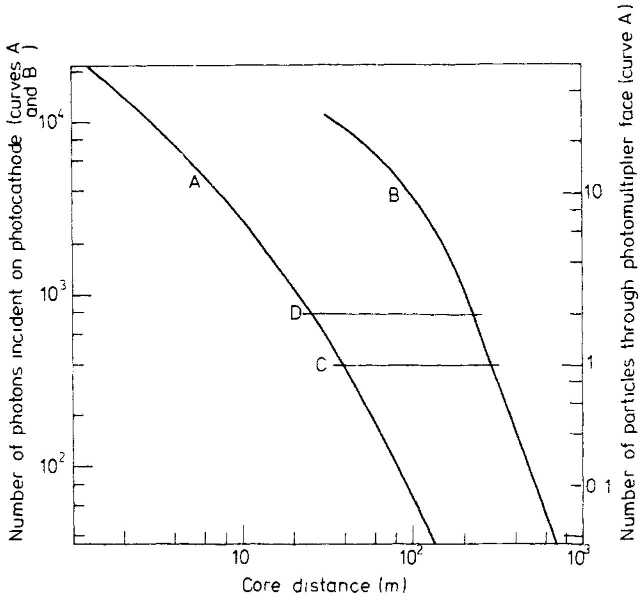

Figure 13. Distribution as a function of distance from the shower core of the average number of photoelectrons liberated from the S11 photocathode of an EMI 9623B photomultiplier by atmospheric (A) and glass (B) Čerenkov photons associated with a vertical shower of size 10^6 particles. The effects of one (C) and two (D) individual shower particles traversing the tube face are indicated.

At distances of more than a few tens of metres from the core of a 10^6 particle shower there is not likely to be more than one charged particle incident on the face of a 7 in photomultiplier. We therefore indicate also the number of photons corresponding to one and two particles traversing the face. The former becomes comparable with the atmospheric Čerenkov signal at about 300 m from the core and such pulses will then be expected to occur in about 1% of all events. It is worth noting that a 3 in tube at 300 m from the core will intercept about one-fifth as many atmospheric photons and produces glass Čerenkov pulses three-tenths as big as a 7 in tube but only in about 0·2% of all events. The situation is somewhat more serious for non-vertical showers, in which case, the pulse amplitude per particle increases with increasing angle whilst the observable atmospheric Čerenkov signal decreases.

6. Conclusions

The general features of the effect of sea level cosmic radiation on photomultipliers are now understood. These features fit a simplified model of Čerenkov radiation in the photomultiplier face quite well and, for the large tubes tested, any other mechanism must have comparatively little effect. Cosmic radiation produces the majority of the large amplitude noise pulses which are observed from the photomultiplier and they can be eliminated by a suitable anti-coincidence device. In cosmic ray shower work where this technique is inappropriate, the effect may be a serious source of anomalous signal fluctuations.

Acknowledgments

The authors gratefully acknowledge the assistance of Mr D Liebing in the theoretical calculations, and Mr J D Kuhlmann for deriving some of the equations used.

Appendix. Calculation of reflection coefficients for Čerenkov radiation at a glass–vacuum interface

Using the techniques of spherical geometry it may be shown that the angle of incidence β, of radiation at an azimuth ϕ is given by

$$\cos\beta = \cos\alpha\cos\theta_{\mathrm{C}} - \sin\alpha\sin\theta_{\mathrm{C}}\cos\phi$$

and the angle θ_{E} made by the electric vector with the interface by

$$\cos\theta_{\mathrm{E}} = \frac{\sin\alpha\sin\phi}{\sin\beta} = \frac{\sin\alpha\sin\phi}{[1-(\cos\alpha\cos\theta_{\mathrm{C}} - \sin\alpha\sin\theta_{\mathrm{C}}\cos\phi)^2]^{1/2}}$$

where α is the angle of incidence of the particle; ϕ, the azimuth angle, is measured from the plane of incidence of the particle in a plane normal to the particle direction (ϕ is the azimuth angle in the plane of the interface); and θ_{C} is the Čerenkov angle.

The geometry is shown in figure 14 and its representation on a spherical surface in figure 15, where N is the normal to the plane of incidence of the radiation.

Reflection coefficients for components of $\boldsymbol{E}$ parallel to the plane of incidence (ρ_{p}) and normal to the plane of incidence (ρ_{n}) were calculated separately at 10° intervals of ϕ from 0° through 360°, and used to calculate the probability (P_{r}) for a photon to be reflected from the front face

$$P_{\mathrm{r}} = \rho_{\mathrm{p}}^2 + \rho_{\mathrm{n}}^2.$$

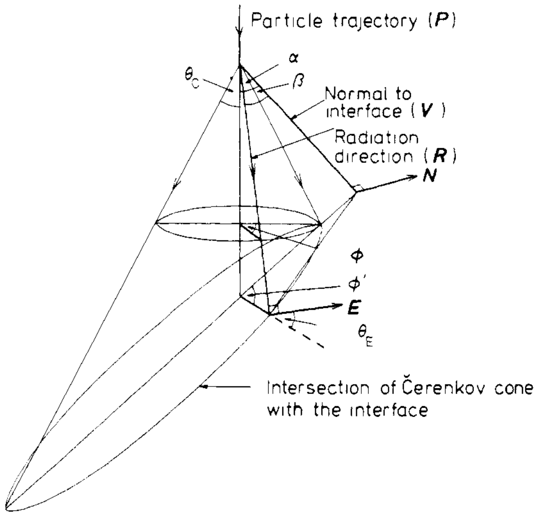

Figure 14. Geometry of Čerenkov cone with intersecting planes having normals at 0° and α° to the particle direction.

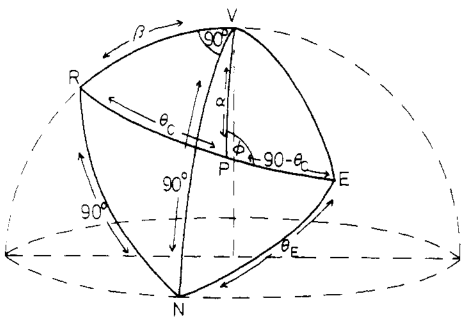

Figure 15. Representation of the intersection with a spherical surface of vectors shown in figure 14.

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