Time Structure of Cosmic-Ray Showers*

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The time structure of extensive air showers at sea level has been measured by coincidence of liquid scintillation detectors and auxiliary Geiger tubes. The standard time deviation relative to the mean of single electrons is found to be 2 ± 2 mμ sec; the same quantity for single particles capable of penetrating 20 cm of Pb is 6 ± 2 mμ sec. The mean delay of penetrating particles relative to electrons is 0.9 ± 1.3 mμ sec.

INTRODUCTION

THE extensive air showers were discovered by Auger and Maze,[1] who observed coincidences between widely spaced Geiger counters, and in most of the subsequent work on this subject it has been implicitly assumed that the shower particles arrive at the detectors simultaneously; usually particles which are not simultaneous within instrumental resolution are not even considered as belonging to the shower. However, it is easy to think of possible causes of delay between shower particles, such as: (a) inclination of the shower axis relative to the plane of observation; (b) difference in velocity of various components; or (c) difference in path lengths due to scattering or emission angles. Some attempts to resolve delays between shower particles have indeed been made, first with Geiger counters,[2–4] and more recently with parallel plate counters[5] and scintillation detectors.[6,7]

Prior to the inception of the present experiment,[8] only the Geiger data were available. Work was therefore begun on the design of large scintillation detectors with an order-of-magnitude improvement in time resolution, i.e., a few times 10^{-9} sec, to be used in a similar exploratory search for delays between shower particles. While our experiment was in progress, extensive results on the same question were published by Bassi, Clark, and Rossi.[7] The data which we have obtained are in essential agreement with theirs, insofar as they confirm the smallness of the delays involved when the detectors are located at small distances. They seem, however, worth presenting, since the two experiments corroborate each other in the points of agreement and may in some respects complement each other.

The main difference between the two experiments is that Bassi *et al.* were mainly interested in delays of type (a) (see above) and therefore used widely spaced detectors, while the present work is a study of effects (b) and (c), performed with detectors close to each other.

EXPERIMENTAL METHOD

A shower was revealed by the quadruple coincidences (within 2×10^{-6} sec) of four detectors, A, B, C, and D. Of these, A and B were fast (tanks of liquid scintillant viewed by photomultipliers), and C and D were slow (Geiger counters). The time interval between the signals in A and B was measured within $\pm 3\times 10^{-9}$ sec whenever an $ABCD$ coincidence occurred. The measurements were made from photographic records of oscilloscope traces displaying the pulses from the fast detectors.

The geometry of the experiment is indicated in Fig. 1, where the location of the detectors is shown, and

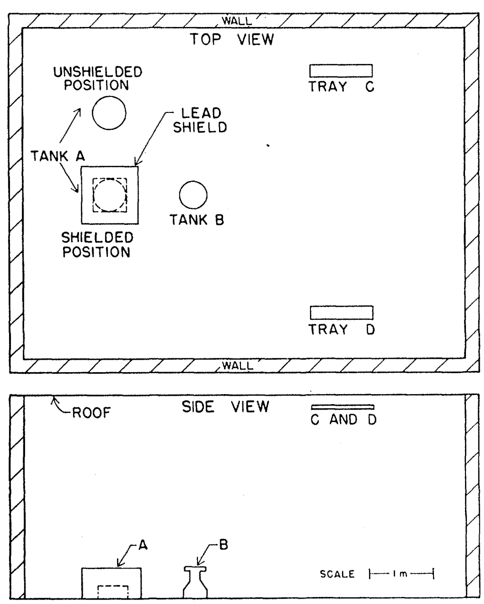

FIG. 1. The detectors and surrounding walls and ceiling. The detector areas are 0.17 m² (A); 0.11 m² (B); 0.2 m² (each of C and D). The mean shower density for $ABCD$ coincidence is computed as 30, 120, and 50 electrons/m² for runs I, II, III respectively. The walls are 25 g/cm² of concrete; the ceiling is 1 g/cm² of Fe plus 5 g/cm² of low-Z material.

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† Submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy. Now at Brookhaven National Laboratory, Upton, New York.

[1] P. Auger and R. Maze, Compt. rend. **207**, 228 (1938).
[2] McCusker, Ritson, and Nevin, Nature **166**, 400 (1950).
[3] Mezzetti, Pancini, and Stoppini, Phys. Rev. **81**, 629 (1951).
[4] V. C. Officer, Phys. Rev. **83**, 458 (1951).
[5] E. Robinson, Proc. Phys. Soc. (London) **A397**, 79 (1953).
[6] J. V. Jelley and W. J. Whitehouse, Proc. Phys. Soc. (London) **66**, 454 (1953).
[7] Bassi, Clark, and Rossi, Phys. Rev. **92**, 441 (1953).
[8] R. Sugarman and S. DeBenedetti, Phys. Rev. **94**, 796(A) (1954).

in Fig. 2, where the fast detectors A and B are described. The experiment was performed at sea level.

Detectors

Detector B was a scintillating tank similar to those of Bassi, Clark, and Rossi. The other fast detector, A, which had to be shielded with 20 cm of Pb on top and sides, was built with a folded optical path in order to reduce its over-all height; it consisted of an annular volume containing the liquid scintillant, covered by a first-surface aluminum mirror to reflect the light from the scintillations to the photocathodes of two multipliers located within the annulus. The liquid scintillant used was a solution of terphenyl in toluene[9] (4 g/l). This was found to respond appreciably faster and with less pulse distortion than the conventional[10] terphenyl+diphenylhexatriene in phenocyclohexane or xylene. The efficiency of the fast detectors was measured as a function of radial distance by using them in coincidence with two small Geiger counters, one above and one below the scintillant. The efficiency for the detection of minimum-ionizing particles was found to be about 95% over most of the active volume, when the circuitry was made sensitive to single photoelectrons at the photocathode.

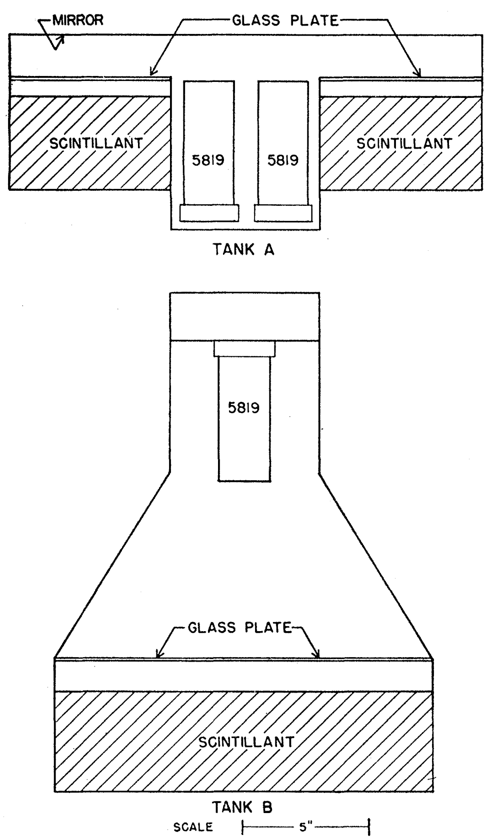


FIG. 2. Schematic views of tanks A and B, which have circular cross sections in plan view. Both are constructed of reinforced spun copper and rest on wheeled cradles. All interior surfaces are reflecting; the glass plates are sealed with Compar gaskets and serve to reduce the (explosive) volume of saturated toluene vapor.

[9] R. F. Post, Phys. Rev. **79**, 735 (1950).
[10] Bittman, Furst, and Kallman, Phys. Rev. **87**, 83 (1953).

Electronics

A block diagram of the circuits is shown in Fig. 3. A slow (2×10^{-6} sec) triple coincidence ACD pulse turned on a sweep of 4×10^{-7} sec duration to display appropriately delayed signals from A and B tanks on an oscilloscope. The presence of a pulse from B on the scope trace insured a quadruple coincidence $ABCD$. The time separation of the pulse peaks from A and B was a measure of the effect investigated.

Had the ACD pulse been used to trigger the sweep directly, inherent time fluctuations in the collection of C and D Geiger pulses would have resulted in a time jitter between sweep start and tank pulses of $\pm2\times10^{-7}$ sec, i.e., of the order of a full sweep duration. The ACD pulse was instead used to gate open a fast (10^{-8} sec) sweep trigger channel through which (after a microsecond) the A pulse passed to start the sweep with a time jitter of about 10^{-9} sec relative to the A display pulse. The time delay of one microsecond was chosen to allow only 10% of all showers to be lost because of late Geiger firing. This necessitated a similar cable delay in the pulse display channels. The increase in rise time caused by this delay was minimized by differentiating A and B pulses with a one-foot length of shorted cable, which kept both the rise and decay time at the screen down to 10^{-8} sec.

The oscilloscope trace contained five pulses (Fig. 4): Two of these, A_1 and $A_1(R)$, were from multiplier 1 in detector A; $A_1(R)$ was the reflection of A_1 in a shorted cable, and appeared about 2.4×10^{-7} sec after A_1. Two more, B and $B(R)$, were from the multiplier in detector B, the second being the reflection of the first as above. Finally, the last pulse, A_2, was from the multiplier 2 in detector A.

The time interval between B and $A_1(R)$ was about 60×10^{-9} sec. Measurement of this interval had to be reproducible within a few percent in order to obtain the required accuracy. The errors in locating and measuring the distances between the positions of the peaks in the photograph of the trace (a traveling-stage microscope was used) were small, corresponding to time errors of the order of a few 10^{-10} sec. However, larger sources of errors could be expected from: (i) variation in sweep speed or in sweep linearity; (ii) distortion of the pulses, which could make the measurement of peak position of doubtful significance.

The distances between the signals A_1 and B and their reflections $A_1(R)$ and $B(R)$ were used to correct for variations in sweep speed and linearity. These reflections provided two known time intervals at different positions on each trace, by means of which it was possible to compute the sweep speed at the position of the pulses to be measured with an accuracy of 1%. This was actually done for each trace. In order to reduce the

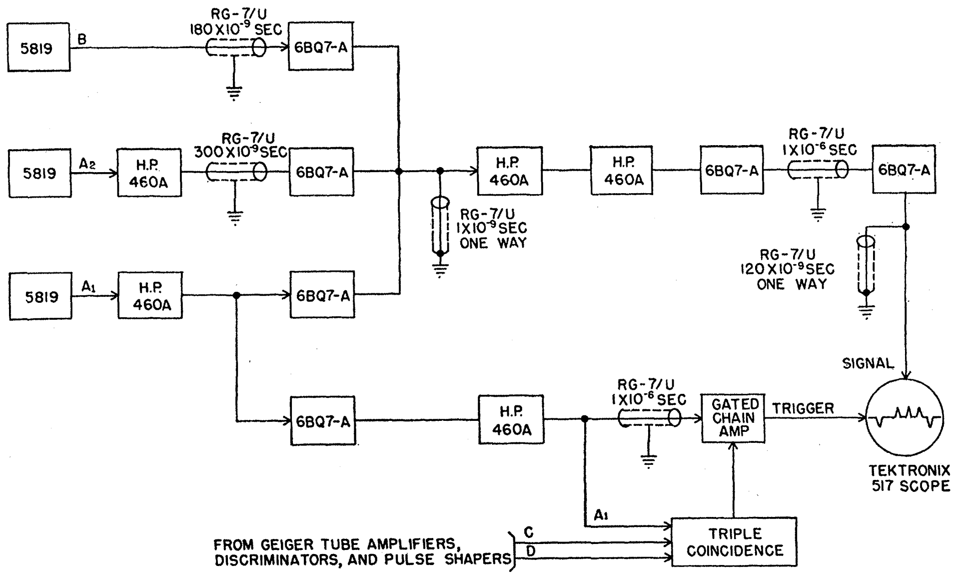


FIG. 3. A block diagram of the fast electronic circuitry. Each chain amplifier (Hewlett-Packard 460A) has a gain of ten; the 6BQ7-A triodes are used for impedance isolation. Scalers (not shown) monitor the number of gates, sweeps, CD coincidences, and phototube noise levels.

errors due to pulse distortion, visibly distorted pulses and after-pulses were not included in the measurement.

Time Calibration

The accuracy of the method was checked in several ways. The measure of success in correcting for the variations in sweep speed and linearity was tested by studying the distribution in the time intervals between pulses $A_1(R)$ and A_2 in all the traces which were used for shower delay measurements. These, coming from two multipliers in the same detector, should always be delayed by the same amount, apart from statistical fluctuation in the processes of pulse formation. On the other hand, the actual measurement of their separation is affected by the same errors in sweep speed calibration as the measurement of the separation between pulses B and $A_1(R)$. The standard deviation in the measured time differences between $A_1(R)$ and A_2 was 3×10^{-9} sec, and part of this is attributable to the fluctuations mentioned above. Furthermore, this standard deviation was practically the same in all runs during the long shower measurements and did not seem to depend on sweep speed variations, indicating that correction for this effect had been properly made.

Another test consisted in the use of the two fast detectors, a Geiger counter and the 20-cm Pb shield as a vertical triple-coincidence telescope for mesons. The time distribution obtained is shown in Fig. 5 (run "0"). The standard time deviation between the pulses of the two fast detectors [B and $A_1(R)$] was $(3.6\pm0.3)\times10^{-9}$ sec. Thus the response of each detector could be timed with an error of $(3.6/\sqrt{2})\times10^{-9}$ sec$=2.5\times10^{-9}$ sec.

MEASUREMENTS OF SHOWER PARTICLE DELAY

Measurements of shower particle delay were performed under three different conditions, which will be discussed separately; the resulting distributions are shown in Fig. 5.

Run I: Both Fast Detectors Unshielded

About 98% of the shower particles in the unshielded detectors were electrons.[11] The striking feature is that the spread of this distribution is practically the same as that observed for the detectors arranged as a vertical telescope, and the standard deviation is (3.2±0.3)

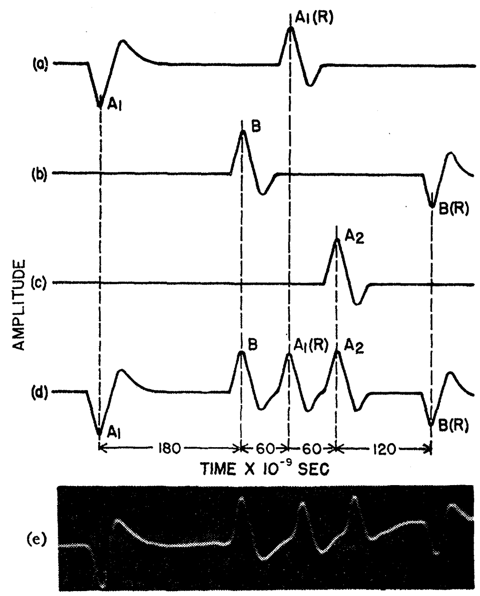


FIG. 4. Oscilloscope traces. (a), (b), and (c) are idealized single phototube pulses from A_1, B, and A_2, respectively; (d) is the resulting composite; and (e) is a photograph of an actual shower event.

[11] Cocconi, Tongiorgi, and Greisen, Phys. Rev. **75**, 1063 (1949).

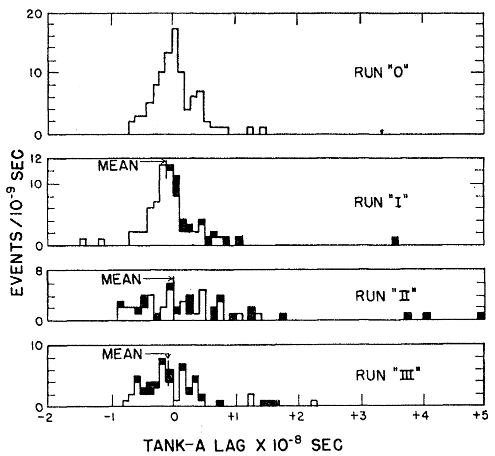


FIG. 5. Histogram of the pulse peak time difference between A and B tanks. The unfilled area represents acceptable events (clean pulses from each of the three tubes). The blocked-in area represents only those rejected shower events with a distorted or missing pulse from one of the two A tubes. The time zero has been chosen to coincide with the mean of run II.

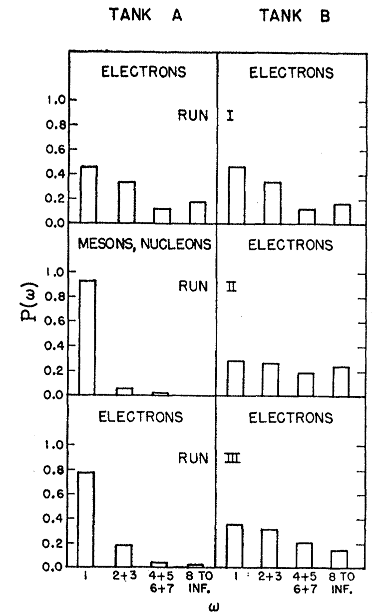


FIG. 6. The normalized Poisson probability, $P(\omega)$, of an $ABCD$ coincidence with ω particles in a tank and one or more in the other three detectors. The ratio of hard to soft particles is taken as 0.023 and both tanks are assumed for simplicity to have the same unreduced area of 0.10 m².

$\times 10^{-9}$ sec. In other words, no significant spread in the arrival of soft shower particles was observed.

For a more detailed comparison of the soft shower distribution with the vertical telescope distribution, one should take into account two effects. The first is that the number of particles contributing to a pulse in each tank is larger in the case of showers. This tends to make that part of the resolving time due to uncertainties in photon and photoelectron collection smaller for the shower run than for the telescope run. The second is the effect of shower axis inclination, which should introduce a spread of about 10^{-9} sec in the shower case[7] even if the shower electrons traveled exactly in the same plane perpendicular to the shower axis.

We may nevertheless conclude from this run that the delays between shower electrons cannot exceed a few millimicroseconds (see Appendix).

Run II: Detector B Unshielded; Detector A Shielded

This experiment was performed with the intent of measuring a delay between the soft and hard components, since it was expected that the heavier particles of the hard component might arrive later.[7] The ratios of quadruple counting rates between this run and the others agree with the ratios computed,[11,12] if one assumes that the soft showers are completely absorbed by the Pb shield. This is in agreement with a theoretical calculation of the effective tank shielding.

A delay between the two components should appear as a shift in the center of mass (mean) of the distributions I and II. The result of the observation is that such shift is small compared to the experimental error. Numerically one would obtain for the mean delay of hard particles relative to soft particles: $(0.9\pm1.3)\times10^{-9}$ sec.

The spread of the time intervals in run II corresponded to a standard deviation of $(7.3\pm0.8)\times10^{-9}$ sec. This result, taken at face value, seems to indicate that the spread in the arrival time of the penetrating particles is larger than the corresponding spread for the soft electronic component, though the mean time of arrival of the two components does not seem to differ.

However, the coincident pulses in the shielded detector seldom correspond to more than one penetrating particle; while the coincident pulses in the unshielded detectors often correspond to more than one particle (see Appendix). This effect could easily increase the observed spreads for penetrating particles by increasing fluctuations in pulse collection time. In order to test this point, we performed run III, as described below.

Run III: Both Fast Detectors Unshielded; A's Area Reduced

The effective area of detector A was reduced to 15% of its total area in order to reduce the number of traversing particles. The area reduction was accomplished by covering most of the scintillant with opaque paper in such a way that the light from the scintillator could reach the multipliers only from a sector of 15% of the total area.

It was computed that the number of coincident particles in detector A should in this case be very similar to those of run II, and that a similar relation should hold for the other tank as well (see Fig. 6).

Under these conditions, no apparent shift in the mean of the time distribution was found, and the standard deviation obtained was $(4.5\pm0.5)\times10^{-9}$ sec, intermediate between runs I and II.

[12] L. Janossy in *Cosmic Radiation* (Colston Papers) (Butterworth's Scientific Publications, London, 1949), p. 103.

DISCUSSION AND CONCLUSIONS

The main conclusion which one can reasonably draw from the results is that our experiments were unable to point out delays larger than a few millimicroseconds between cosmic-ray shower particles. The mean arrival times of the soft and hard components seem to be the same within 10^{-9} sec. In the appendix we derive a time dispersion of $(2\pm 2)\times 10^{-9}$ sec for single electrons and $(6\pm 2)\times 10^{-9}$ sec for penetrating particles. This is an indication that the time spread of the hard component is greater than that of the soft. If this is true, it could be explained by assuming that the mean delay of the hard particles (mostly due to their velocity being smaller than c) is equal to the mean delay of the electrons (mostly due to multiple Coulomb scattering); but that the spread of the time distribution from the mean is larger for the hard component than for the electrons because of the different processes responsible for the delays in the two cases.

The number of events finally used in this work is not large (65 for run I, 38 for run II, 42 for run III) and any rare delayed event would have escaped observation. However, we did not think it worth while to go through the labor of collecting more data because of the uncertainties in correcting for the instrumental resolution. Therefore this experiment is a measure of mean delays and dispersions, but is not meant to detect delayed components of weak intensity.

APPENDIX

From the results obtained in runs I, II, and III we seek a value for σ_e, the s.d. (standard deviation relative to the mean) of the arrival times of single electrons measured in an imaginary plane normal to the shower axis, and for σ_μ, the same quantity for single hard particles (mostly muons). From a given tank we obtain a contribution $\sigma_{e,\mu}$ (i.e., σ_e or σ_μ), depending on whether the tank is unshielded (e) or shielded (μ).

The computation has been carried out assuming:

(i) that all the variables contributing to the s.d. σ_{AB} of the difference in time between tanks A and B are statistically independent;

(ii) that the s.d. of the instrumental error in the measurement of a single particle time, σ_i, is due entirely to dispersion in tank and phototube collection times and has the value $[(3.6/\sqrt{2})\pm 0.2]\times 10^{-9}$ sec, as found from the telescope run;

(iii) that the part of the observed dispersion which is due to the inclination of the shower axis has a s.d. σ_θ given by[7]

$$\sigma_\theta \simeq [\langle \sin^2\theta\rangle_{\mathrm{Av}}]^{\frac{1}{2}}\times (d/c) = 1.2\times 10^{-9}\ \text{sec},$$

where θ is the projected zenith angle, d is the lateral tank spacing, and c is the velocity of light;

(iv) that a tank pulse peak occurs at the average arrival time of all its shower particles, each affected by its own instrumental error.

Then the s.d. $\sigma_{AB}(\omega_A,\omega_B)$ which one would experimentally observe for showers with ω_A particles in tank A and ω_B particles in tank B is given, for each of the three runs, by an equation of the form

$$\sigma_{AB}^2(\omega_A,\omega_B)=\omega_A^{-1}(\sigma_{e,\mu}^2+\sigma_i^2)+\omega_B^{-1}(\sigma_e^2+\sigma_i^2)+\sigma_\theta^2. \quad (1)$$

In order to compare σ_{AB} with its experimental values, it must be averaged over the distribution in particle densities ω_A and ω_B. Assuming that σ_i, σ_θ, and $\sigma_{e,\mu}$ are independent of ω, we then have

$$\langle\sigma_{AB}^2\rangle_{\mathrm{Av}}=\langle\omega_A^{-1}\rangle_{\mathrm{Av}}(\sigma_{e,\mu}^2+\sigma_i^2) +\langle\omega_B^{-1}\rangle_{\mathrm{Av}}(\sigma_e^2+\sigma_i^2)+\sigma_\theta^2, \quad (1\text{a})$$

where

$$\langle\omega_A^{-1}\rangle_{\mathrm{Av}}=\sum_{\omega=1}^{\infty} P(\omega_A)/\omega_A,\ \text{etc.}$$

We computed[12] the probabilities $P(\omega)$ from shower theory, and obtained the values shown in Fig. 6. These, within the rather poor resolution, agree with the measured pulse heights recorded for each shower event.

Introducing in (1a) the experimental values of $\langle\sigma_{AB}^2\rangle_{\mathrm{Av}}$ and σ_i, and the computed values of σ_θ and $\langle\omega^{-1}\rangle_{\mathrm{Av}}$, one obtains a value of σ_e from each of runs I and III. From run II, one finds σ_μ in terms of σ_e. This last relation is particularly simple because of the prearranged similarity of the ω distribution in runs II and III (see Fig. 6). The results are that

$$\sigma_e=(2\pm 2)\times 10^{-9}\ \text{sec},\quad \sigma_\mu=(6\pm 2)\times 10^{-9}\ \text{sec},$$

where the errors include an estimate of the uncertainties in the treatment.

Within the (large) stated error, the numerical results are probably insensitive to the nature of the previous assumptions. It has been proposed,[7] for example, that (iv) be replaced with the extreme assumption:

(iv-a) only the pulse peak associated with the first tank particle is recorded.

Let $p_\omega(t)$ be the normalized probability of this peak at time t for a total of ω tank particles in a normally incident shower. Then

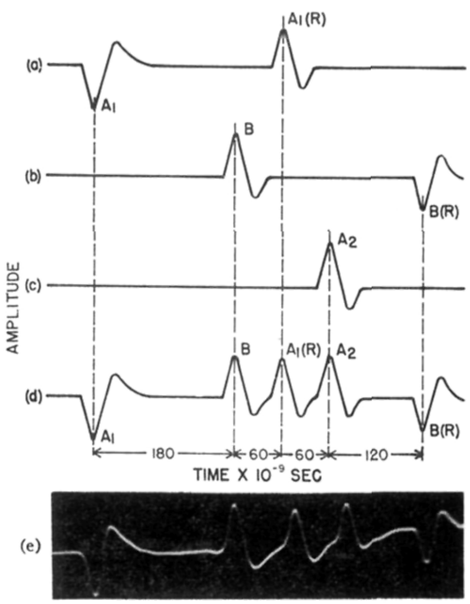
$$p_\omega(t)=N(\omega)p_1(t)\left[1-\int_{-\infty}^{t} p_1(t)dt\right]^{\omega-1}, \quad (2)$$

where $N(\omega)$ is the normalizing factor.

Assuming a reasonable form for $p_1(t)$, and one that also includes instrumental error, let

$$\begin{aligned} p_1(t)&=\sigma^{-1}e^{-t/\sigma} \quad && t\geqslant 0\\ &=0 && t<0, \\ \sigma^2&=\sigma_{e,\mu}^2+\sigma_i^2. \end{aligned} \quad (3)$$

From the foregoing, $\sigma_{AB}(\omega_A,\omega_B)$ is now the root-mean-square sum of σ_θ and the standard deviations of $p_\omega(t)$ for each tank. These standard deviations may easily be found as a function of ω and σ from (2) and (3). Averaging $\sigma_{AB}(\omega_A,\omega_B)$ over ω as before, one then obtains an equation for $\langle\sigma_{AB}^2\rangle_{\mathrm{Av}}$ differing from (1a) only in that for each tank $\langle\omega^{-1}\rangle^2_{\mathrm{Av}}$ is replaced by $2\langle\omega^{-2}\rangle_{\mathrm{Av}} -[\langle\omega^{-1}\rangle_{\mathrm{Av}}]^2$. These new constants (as computed from Fig. 6) are sufficiently close to the old ones to give unchanged values for $\sigma_{e,\mu}$.



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