THE RESIDUAL RANGE OF DELAYED PARTICLES IN EXTENSIVE AIR SHOWERS

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Summary

The arrival times of the penetrating particles of extensive air showers relative to that of the electrons have been studied by means of short reaction time Geiger counters. A 50 channel hodoscope has been used to identify the penetrating particles and measure their residual ranges where these lay between 15 and 30 cm of lead. From observations on 782 showers of median density 70 particles m^{-2} in which a penetrating component was detected, it was deduced that between 3 and 9 particles in 10^4 shower particles from showers of median density 28 particles m^{-2}, have delays $<5\times10^{-8}$ sec and are able to penetrate 15 cm of lead. It follows that 81–94 per cent. of the delayed particles found by Jelley and Whitehouse (1953) without the use of absorbers, must be stopped by 15 cm of lead. This indicates a height of production below $0\cdot8$ km for at least half of these particles.

Two of the penetrating delayed μ-mesons were stopped in the lead, and their heights of production calculated to be $1\cdot0^{+0\cdot7}_{-0\cdot4}$ km and $4\cdot7^{+4\cdot5}_{-2\cdot2}$ km on the assumption that the delays were due to velocity differences. Thirty other μ-mesons for which the individual time lags were not significant were also stopped in the lead and gave a mean delay indicating production below an altitude of 250 m. The remaining 208 μ-mesons which did not stop could not be assigned a height of production.

One delayed proton was found in the total of 29 delayed events observed, and nine events could have been oblique particles lagging on the electrons by virtue of path differences.

I. Introduction

Some particles in extensive air showers can arrive at the plane of observation later than others if they have travelled from high in the atmosphere with a slightly lower velocity, or if their path lengths have been different. It is to be expected that the heavier shower particles, the mesons and nucleons, will have the largest delays. If a delayed particle is identified and its residual range measured as well as its delay with respect to the shower electrons, its height of production can be found provided the delay was due to a velocity difference. In this way it should be possible to find the distribution of the heights of production and energies at production for the low energy μ-mesons in air showers. If, in a simple analysis, the fact that mesons traverse the early part of their path as π or heavier mesons is neglected, an overestimate of the height of production will result.

Several previous investigations have been made into the delayed particles in air showers. McCusker, Ritson, and Nevin (1950) found no particles delayed

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by more than 150 cμsec (i.e. 150×10^{-8} sec). Mezzetti, Pancini, and Stoppini (1951) found penetrating particles with delays between 10 and 120 cμsec. The mean delay of particles able to penetrate 10 cm of lead was found by Officer (1951) to have an upper limit of 2 cμsec. This latter work has now been continued after developing short reaction time Geiger counters. Recently Jelley and Whitehouse (1953) using a large unshielded liquid scintillation counter have found 0·6 per cent. of shower particles to have delays between 3 and 70 cμsec. The distribution of delays could be represented by an exponential function with half the delays less than 10 ± 2 cμsec. Three large liquid scintillation counters have recently been used by Bassi, Clark, and Rossi (1953) to study the distribution of arrival times of both the electrons and the penetrating particles at sea-level. They found that at a given instant most of the electrons lie in a flat disk between 1 and 2 m thick, and the particles able to penetrate 20 cm of lead follow less than 3 m behind in a disk between 2 and 3 m thick. With widely spaced counters they studied the angular distribution of shower axes and the curvature of shower fronts. In the present work time lags arising from the inclination of showers or curvature of shower fronts are not important, since the counter tray spacing was only 2 m.

II. Apparatus and Procedure

The showers were detected by a set of three Geiger counter trays arranged at the apices of a 2 m equilateral triangle and connected in threefold coincidence with a resolving time of approximately 1 μsec. Two of the trays were composed of short reaction time counters and connected to the two channels of the time interval measuring apparatus. One of the timing trays was shielded with 15 cm of lead and the other was unshielded. The third tray contained ordinary counters and supplied pulses to the coincidence circuit only. Under the shielded tray were layers of lead and hodoscope counters for residual range measurement and penetrating event identification. A threefold coincidence caused the time interval between the pulses from the two timing trays to be recorded at the same time as the configuration of hodoscope counters discharged.

The shielded timing tray, 359 cm^2 in area, consisted of 26 short reaction time counters with nickel cathodes 4·6 mm in diameter (Officer and Eccles 1954). The unshielded timing tray, 450 cm^2 in area, consisted of 30 short reaction time Maze-type counters with glass cathodes 5 mm in inside diameter. The unshielded third tray was 583 cm^2 in area, and consisted of 10 conventional counters 2 cm in diameter.

The small glass counters had anode wires of tungsten 0·004 in. in diameter mounted accurately on the axis of soft glass tubes of 5 mm bore. A layer of "Aquadag" painted on the outside of the tubes and extending over 30 cm of their length was connected to the negative voltage supply. Earthed guard rings of "Aquadag" 1 cm from the ends of the cathode coating prevented electrical leakage from the negative supply over the surface of the glass to the signal circuits connected to the anode wires. A coat of clear "Glyptal" protected the insulating glass surfaces and the "Aquadag". Six of these counters were mounted in a plane and sealed to the same quenching mixture

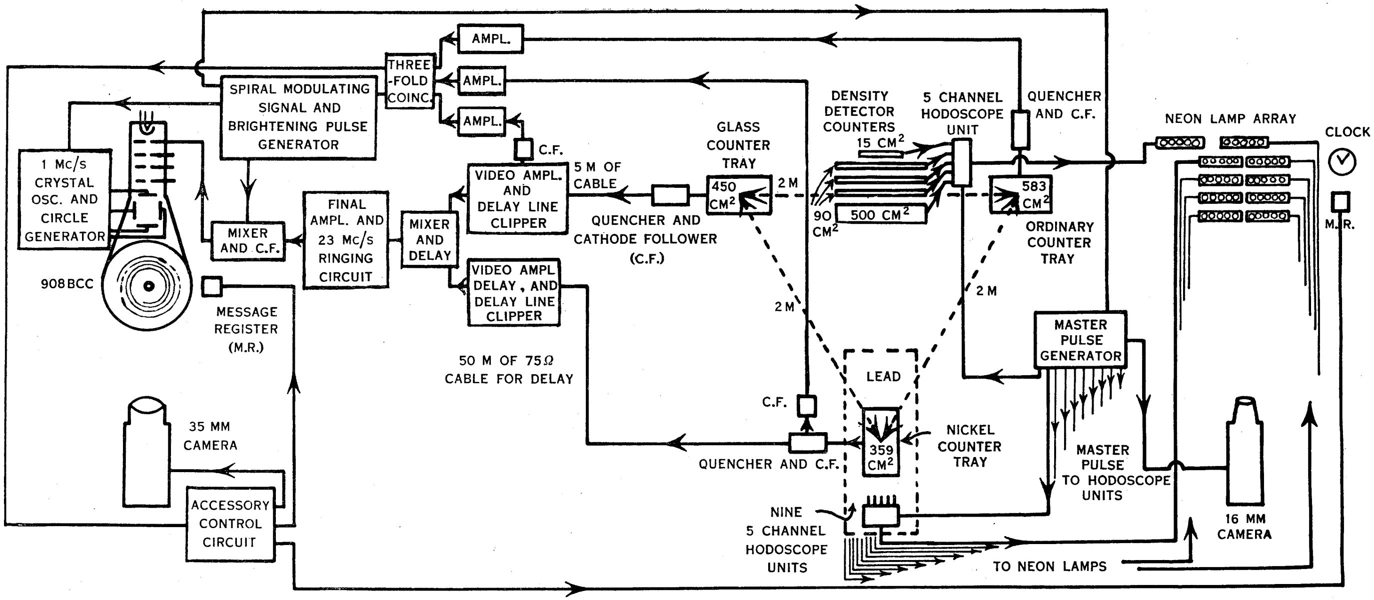

Fig. 1.—Block diagram of circuits and plan of counter arrangement.

reservoir, a soft glass cylinder 4 cm in diameter and 43 cm long. The processing included baking at 200 °C under vacuum. The filling was 22·5 cm of 9 : 1 argon-ethyl formate mixture for the same starting and working voltages, 970 and 1120 V, as for the nickel counters. All the counters in each tray were connected in parallel and provided with a single external quenching circuit per tray to prolong their life. Direct coupling to the quenching circuit made the anode wires 300 V above ground potential.

The performance of the glass counters was similar to that of the nickel counters, although, as will be shown in Section 3 (*a*), the end effects were greater. The relative reaction time distribution for the two full trays, one of glass and one

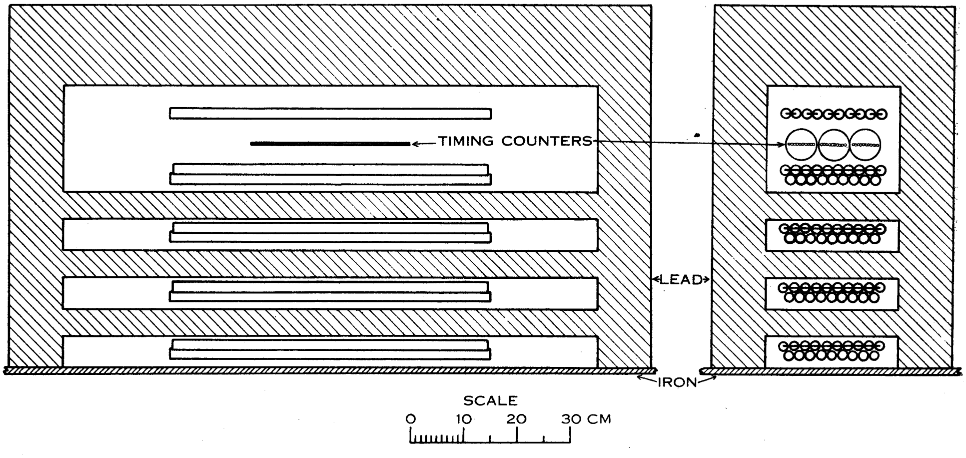

Fig. 2.—Counter and lead arrangement for residual range measurement, penetrating event identification, and timing.

of nickel counters, had only slightly greater spread than that reported by Officer and Eccles (1954) for much smaller trays of nickel counters operated in parallel. The standard deviation of the distribution was $1 \cdot 6 \pm 0 \cdot 06$ cμsec.

The two short reaction time trays were connected to the timing channels as shown in the block diagram of Figure 1. The timing apparatus was similar to that described earlier by Officer (1951), but brilliance modulation instead of radial deflexion was used to put the timing information on the spiral time base as outlined previously (Officer and Eccles 1954).

Figure 2 shows the arrangement of the hodoscope counters around the nickel timing tray, and the disposition of the lead for shielding and residual range measurement. Counters joined by horizontal lines are connected to the same hodoscope channel. The rest have one hodoscope channel each. The individually connected counters gave information about the nature of the penetrating event, and the guard layers made the determination of residual range more certain. A hodoscope resolving time of 20 μsec was used. Residual range measurements were confined to the 15–30 cm of lead interval, but calculation showed that mesons having these residual ranges and originating higher than a few kilometres above the apparatus, should have measurable time lags. A thickness of 15 cm of lead was chosen as the top shield, rather than the 20 cm thickness usually used to isolate the penetrating component of air showers. The aim was to detect as many as possible short residual range, possibly highly delayed, particles. The hodoscope was relied upon to reveal the cases in which these particles were accompanied by other phenomena.

A simple shower density detector consisting of five counters connected to hodoscope channels was placed as shown in Figure 1. Its chief purpose was to enable an estimate of the number of hits scored on the unshielded timing tray to be made. This allowed recognition of cases in which an apparently late pulse from the shielded tray could be due to the selection of the shortest of several counter reaction times from the unshielded tray, rather than to a genuinely delayed single penetrating particle striking the shielded tray.

The photographs of the cathode-ray tube trace and those of the hodoscope information displayed on neon lamps were correlated by means of message registers appearing in each photograph. The time intervals were read from the photographs of the spiral trace by projecting them on to a vernier reading circle, and measuring between the sharp trailing edges of the bright dashes produced by the timing pulses.

The timing pulses were separated by an artificial delay to avoid overlapping when short intervals were measured, and they were both delayed sufficiently to enable time lags up to 30 ± 10 cμsec to be measured. The fluctuation in the length of time base available for measurement was due to the spread in the reaction times of the ordinary counters in the third tray. The time origin was found by placing the two unshielded trays on top of the lead shielding of the nickel tray, and recording the pulses produced by penetrating particles of the normal cosmic ray flux passing through the trays. Three to four hundred observations were required, and a time of flight correction was applied. The origin was determined in this way at intervals throughout the run, and a histogram containing the whole 2064 of these observations is shown in Figure 3 (*a*).

During some of the origin tests the particles selected by the counter telescope were used to test the performance of the hodoscope. The main performance monitoring of the whole equipment was a daily routine of waveform checking. Since the spiral time base was generated from the output of a 1 Mc/s quartz crystal oscillator no time base calibration was required.

III. Results

(*a*) *The Abundance of Delayed Events*

A total of 782 showers was recorded in 1543 hr. The time interval histogram for all these showers, except a few in which a cathode-ray "ghost image" obscured the record, is shown in Figure 3 (*b*). The histogram of Figure 3 (*a*) contains all the time origin observations taken with single mesons passing through both timing trays. It is normalized to the same area as that of the shower histogram and its mean, after a 10^{-9} sec time of flight correction, is taken as the time origin for the shower histogram.

The time intervals referred to this origin are the differences between the times of detection of the pulses from the two timing trays. Positive intervals indicate that the pulse from the shielded tray was the later, and negative intervals indicate that the unshielded tray gave the later pulse.

It can be seen that the shower histogram has a greater spread than the origin histogram, especially at the base. If delays greater than 5 cμsec are considered significant, 29 showers had significantly delayed penetrating particles. If exceeding $5 \cdot 4$ cμsec, the extreme upper limit of the origin observations, is taken as the criterion of significance there are 23 significantly delayed events.

There is also an extension of the shower histogram in the negative direction, but there is a similar tail on the origin distribution although it has a smaller fraction of the observations in it. The extra negative lags could not be due to a genuinely delayed particle discharging the unshielded tray and a prompt penetrat-

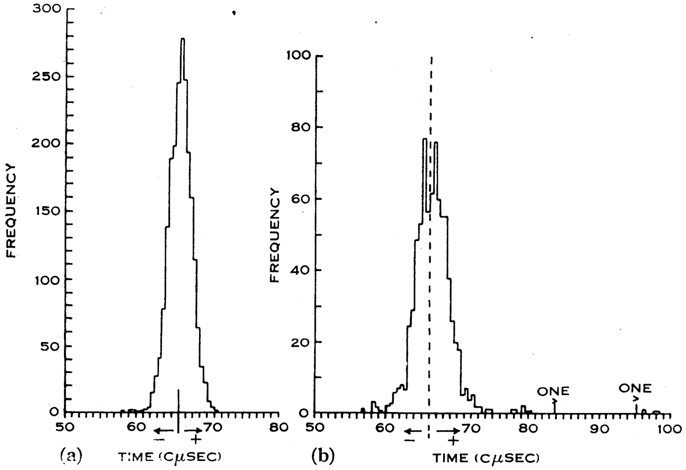

Fig. 3.—Time origin and total shower time interval histograms. (*a*) Origin histogram, 2064 observations; (*b*) all showers histogram, 776 showers (one $24 \cdot 9$ cμsec interval and two cases with one pulse only).

ing one striking the shielded tray, if the total abundance of delayed particles is as found by Jelley and Whitehouse. Only one negative lag would be expected from this cause. By selecting with a counter telescope a beam of penetrating mesons passing through the ends of the counters in the unshielded tray, it was shown that the negative tail could be due to an end effect in the small diameter glass counters. The counter telescope arrangement used for the time origin observations gave a smaller probability for particles passing through the counter ends than did the shower arrangement. A similar test for end effect in the nickel counters of the shielded tray showed that the effect was less marked for these counters. The positive tail of the test histogram exhibited an almost linear decrease from 4 cμsec to an upper limit of $7 \cdot 3$ cμsec, whereas the negative tail found in the test of the glass counters had a similar shape to that in Figure

3 (*a*) and extended as far as $-15\cdot3$ cμsec with no indication that a limit had been reached.

When the different end structures of the two counter types are considered it can be seen that the great difference in behaviour is reasonable. The sensitive length of the nickel counters is terminated by the $0\cdot002$ in. diameter anode wire entering a " Monel " capillary tube $1\cdot7$ mm in outside diameter with a hemispherical end. The nickel cathode cylinder is $4\cdot6$ mm in inside diameter. In the glass counters the sensitive length terminates more slowly. The $0\cdot004$ in. diameter anode wire emerges from the " Aquadag " coated cathode section of the 5 mm bore glass tube and traverses a 1 cm uncoated length before passing through an earthed guard ring. The distribution of potential over the uncoated glass governs the form of the electric field at the ends. The larger capacity of the glass counters, resulting from the use of thicker anode wires, may also have an influence on the importance of end effects, and different discharge propagation velocities could result in different lengths of end section being affected.

If exceeding $7\cdot3$ cμsec is taken as the criterion for significance of delayed events, the result should be a safe lower limit to their abundance, as end effect delays of $7\cdot3$ cμsec are rare even when a beam passing through the end section is selected. In fact, as will be shown in Section III (*b*), much of the positive tail below $7\cdot3$ cμsec is due to multiple hits on the unshielded tray. We are left with a lower limit of 11 significantly delayed events. The upper limit remains at 29. Then from the expression for the rate of detection of showers containing significantly delayed penetrating particles,

$$\int_0^\infty K\Delta^{-\gamma}(1-e^{-S_1\Delta})(1-e^{-S_2\Delta\varepsilon})(1-e^{-S_3\Delta})\,d\Delta \quad \mathrm{hr}^{-1},$$

where $K=787$, $\gamma=2\cdot4$, and S_1, S_2, S_3 are the tray areas, the fraction ε of shower particles significantly delayed and able to penetrate 15 cm of lead lies between 3 and 9 in 10^4. The values of K and γ are those given by Singer (1951). This calculation assumes that ε is independent of the shower density Δ. The calculated median density of the penetrating extensive showers detected is 70 particles m^{-2}, but it could be considered that the showers that would discharge the three trays if there was no shield were being searched for penetrating delayed particles. The calculated median density of these showers is 28 particles m^{-2}.

The complete shower histogram contains one large negative lag of $-41\cdot1$ cμsec and two cases in which only the pulse from the shielded tray appeared on the trace. It is very likely these are due to late quenching circuit pulses from the unshielded tray. With only one quenching circuit to a whole tray of counters an occasional counter discharge will occur before the quenching circuit has fully recovered from the previous one, and therefore give rise to a delayed quenching pulse. Normally the quenching pulse arrives within the clipping time of the delay line clipper and is not resolved from the counter pulse, but a late quenching pulse should appear as a third pulse on the trace. However, since the coincidence circuit requires the large amplitude of the quenching pulse, the time base starts late on these occasions and only one or two pulses may be seen. Since the counting rate, $7\cdot1$ sec^{-1}, in the heavily shielded nickel tray was low, and that of the glass tray, 44·9 sec^{-1}, very high, the effect was confined to the latter tray. Radioactive potassium in the soft glass (A. G. Fenton, personal communication), as well as lack of shielding, was responsible for the high rate. About 1 in 200 quenching pulses from the glass tray was observed to be late. It follows from this and the counting rates that 1 in 1240 from the nickel tray would be late, and since there were only 782 showers observed the effect could not make a significant contribution to the delayed events.

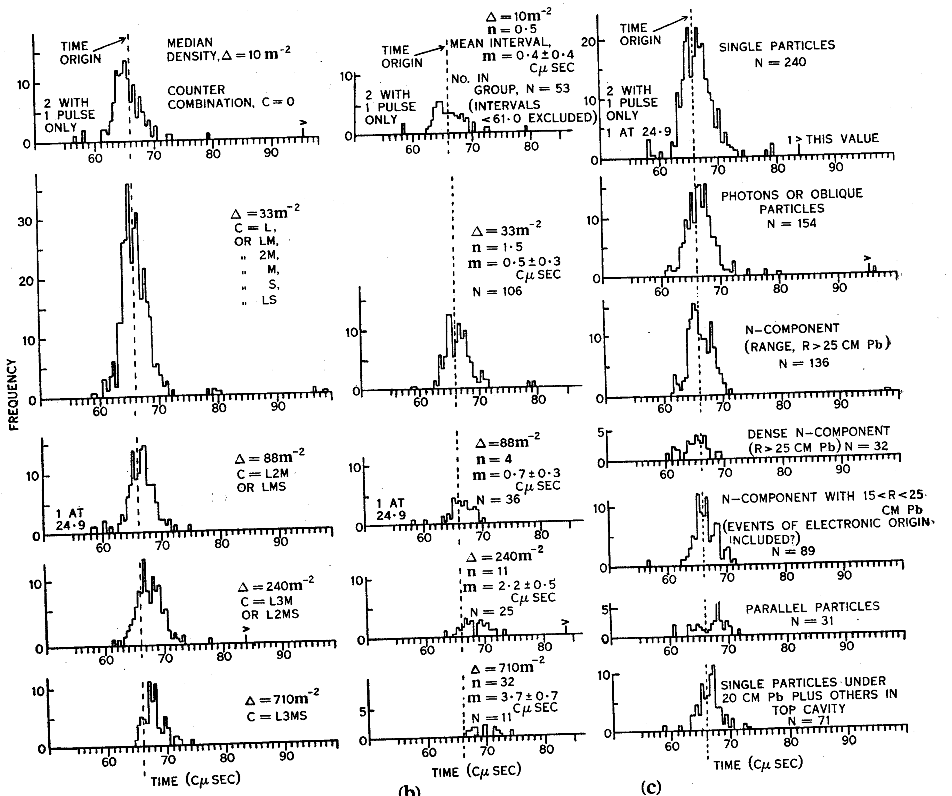

Fig. 4.—Analysis of time intervals according to shower density and nature of penetrating event. (*a*) Density analysis; (*b*) density analysis for single penetrating particle events; (*c*) nature of penetrating event analysis. n is the average number of hits on an area equal to that of the unshielded tray in showers of density Δ. In (*c*) there were 17 observations in a miscellaneous group.

Accidental coincidences were also insignificant. Calculation shows that the probability that there are no accidentals in the 782 showers is 0·6.

(*b*) *The Influence of Shower Density*

Figure 4 (*a*) shows an analysis of the shower results according to the density information supplied by the density detector group of counters. The calculated median shower density is quoted for each histogram and also the combinations of large, medium, and small density detector counters discharged. The median number of hits scored on the unshielded tray by showers of the stated median densities, detected or not, are also quoted. A progressive shift in the positive direction of the histogram mean values as the shower density increases is clearly shown. This effect is mainly responsible for the broadening of the total shower histogram of Figure 3 (*b*). The effect arises from the fact that in showers of high density the unshielded timing tray is hit by many more particles than the shielded tray which often receives only one hit. This means that the shortest of many counter reaction times is chosen from the unshielded tray, giving an abnormally short reaction time and making the pulse from the shielded tray appear to be late. This effect has been noticed earlier by Officer (1951) and has been discussed more fully by Officer and Eccles (1954) for the case of simultaneous hits. Here of course any spread in the arrival times of the particles will modify the effect.

(*c*) *The Nature of the Delayed Events*

In Figure 4 (*c*) the time intervals are analysed according to the information on the nature of the penetrating events given by the hodoscope. Most of the positive intervals greater than 5 cμsec are found in the single particle group. This group consists of cases in which a single penetrating particle hit the shielded timing tray and continued into the lead layers below. From the rarity of interactions produced in the lead by these particles they were identified as μ-mesons.

The positive intervals greater than 7·3 cμsec are divided about equally between the single particle group and the very oblique particle or photon group. In the latter group either no hodoscope counter at all or just one in the top lead cavity was discharged. These events could equally well be explained as long range photons from burnt out cascades in the 15 cm of lead above (Greisen 1949) or very oblique particles. The photons should predominate, but it is possible that the significant time lags were produced by oblique particles that arrived late through having traversed a large component of path perpendicular to the shower axis.

There was one significantly late event in the *N*-component group. In this event a particle with range greater than 30 cm of lead produced secondary particles that could penetrate 10 cm of lead. If the particle was a μ-meson it would have required an energy of at least several kMeV, and could not have travelled sufficiently slowly to lag 32 cμsec on the shower electrons even if it came from the top of the atmosphere. It was considered likely to be a proton which could have arrived from an altitude of 20 km with this lag and a residual energy of about 7 kMeV.

It will be noticed that the very dense *N*-component group, in which most of the shielded counters were fired even under 30 cm of lead, shows an excess of negative lags. This is a density effect of opposite sign to the previous one because the shielded tray frequently received many more hits than the unshielded one.

Figure 4 (*b*) shows the single particle group analysed according to shower density. As before the upward shift in the mean values with increasing shower density is clear. It will be noticed, however, that there are both large and small, possibly significant positive lags in the low density groups where multiple hits on the unshielded tray would be very unlikely.

(d) *Residual Ranges and Heights of Production*

The delays of μ-mesons relative to particles travelling with virtually the velocity of light have been calculated for various residual ranges in lead at sea-level and common starting heights. These delays, shown in Figure 5, could apply to delays of μ-mesons relative to the shower electrons if it is assumed that the nuclear cascade, which gives rise to both the electrons and the mesons, has kept pace with the electrons down to the point of formation of the mesons

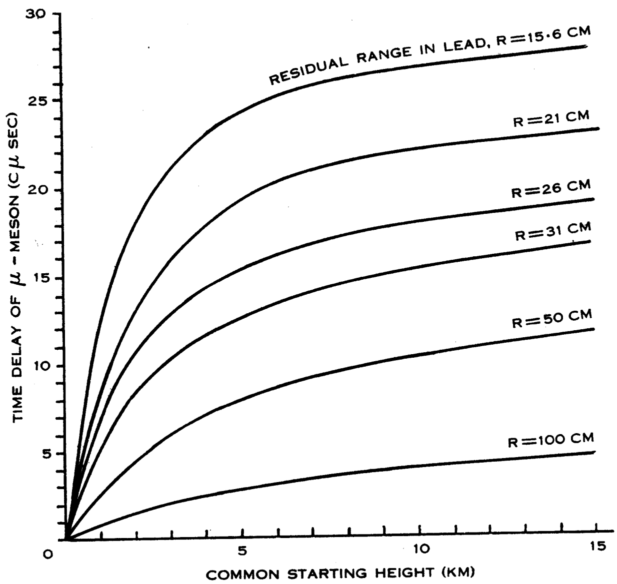

Fig. 5.—μ-Meson delays with respect to a particle having virtually the speed of light plotted against their common starting height for various residual ranges in lead.

in question. The fact that the mesons will have traversed the early part of their path as π or heavier mesons has been neglected. These simplifications could lead to an overestimate of the height of production of a meson with given delay and residual range.

Of the particles with significant time lags only two were brought to rest in the lead below the shielded tray. Both had ranges between 25 and 30 cm of lead and both were considered to be μ-mesons. The first had a delay of $8\cdot4\pm1\cdot6$ cμsec where the error quoted is the standard deviation of the time origin distribution, but the delay should be reduced by about $2\cdot5$ cμsec as it came from the 710 particles m^{-2} shower density group. With as many as 32 hits on the unshielded tray its reaction time should be very small, and the time origin distribution under these conditions should be roughly rectangular extending from 0 to about 5 cμsec, the approximate extreme value of the normal origin distribution (Officer and Eccles 1954). With such a large number of hits the time required to collect sufficient charge for detection may be reduced as well as the electron drift time, making a somewhat larger correction necessary. If the lag is taken as $5\cdot9\pm1\cdot6$ cμsec the height of production would be $1\cdot0^{+0\cdot7}_{-0\cdot4}$ km above the apparatus, and the extreme range of heights $0\cdot1$–$3\cdot6$ km if ±5 cμsec is taken as the extreme timing error.

The second particle came from a low density group and its lag of $13\cdot4\pm1\cdot6$ cμsec needed no correction. Its height of production was $4\cdot7^{+4\cdot5}_{-2\cdot2}$ km with extreme limits of $1\cdot4$–13 km.

There were 30 single particles without significant lags stopped* in the lead, their residual ranges lying between 15 and 30 cm. They were all considered to be μ-mesons. Eighteen of them came from low density groups and gave a mean lag of $0\cdot4\pm0\cdot5_7$ cμsec. It should be safe to say that the lag was less than $1\cdot5$ cμsec and their mean height of production therefore less than 250 m.

The mean lag for the whole single particle or μ-meson group analysed in Figure 4 (*b*) is $0\cdot8_8\pm0\cdot1_7$ cμsec. The negative lags in excess of -5 cμsec were omitted, but if the positive lags greater than 5 cμsec are also omitted there is still a positive mean lag of $0\cdot5_3\pm0\cdot1_4$ cμsec. This positive value could easily be due to the influence of the density effect, but the group with median density 10 particles m^{-2} should be free from this uncertainty. The mean value of this lowest density group is $0\cdot4_5\pm0\cdot4$ cμsec with the large negative lags omitted and $-0\cdot0_6\pm0\cdot3$ cμsec with the large positive lags also omitted. The fact that the standard deviation of this group, $3\cdot0\pm0\cdot3$ cμsec is significantly greater than $1\cdot6\pm0\cdot06$ cμsec for the origin distribution may be related to the thickness and spacing of the electron and meson shower disks found by Bassi, Clark, and Rossi (1953).

IV. Discussion

The present results show that between 3 and 9 in 10^4 air shower particles are significantly delayed and are also capable of penetrating at least 15 cm of lead. "Significantly delayed" could be interpreted to mean that the particles have delays greater than 5 cμsec on the average, provided the abundance of delayed particles does not vary too rapidly with delay in the region 0–10 cμsec, the approximate extreme width of the time origin distribution. From the results obtained by Jelley and Whitehouse (1953) without absorbers, 47 in 10^4 shower particles are delayed more than 5 cμsec with respect to the electrons. This means that between 81 and 94 per cent. of the delayed particles in air showers are absorbed by 15 cm of lead. The showers detected by Jelley and Whitehouse had about 1/3 of the density of the present ones, but they found no correlation between delay and density.

* In the group of 32 particles recorded as stopped in the lead six could have been erroneously included through their having escaped from the ends of the hodoscope array. This was calculated from the zenith angle distribution of penetrating shower particles obtained from the hodoscope records, and to be published later together with other data on the penetrating component of air showers.

The upper limit to the residual range of the bulk of the delayed particles thus obtained allows something to be learned about their height of production. If the particles are μ-mesons and the delays due to velocity differences, at least half of them must have been produced below an altitude of $0 \cdot 8$ km, since Jelley and Whitehouse found that half of them had delays less than 10 cμsec. Similarly at least three-quarters of them were produced below $2 \cdot 7$ km, but the present upper limit to the residual range would permit production of the highly delayed particles at almost any height. If the delays are due to oblique particles having very different path lengths from the electrons, a low height of origin would still be indicated. If the delayed particles are protons rather than μ-mesons the heights of production would be very much lower, but it seems likely that Jelley and Whitehouse would have obtained larger scintillation pulses had the particles been protons with residual range less than 15 cm of lead.

The present results for μ-mesons with residual ranges between 15 and 30 cm of lead also lead to low heights of origin, less than 250 m on the average. Little can be said about the heights of production of the 208 μ-mesons that did not stop in the lead. The mean delay for the whole μ-meson group $0 \cdot 8_8 \pm 0 \cdot 1_7$ cμsec agrees with that found by Bassi, Clark, and Rossi (1953), but this may be a coincidence as their result should be free from the influence of multiple hit effects which are important here when dense showers are included. The mean of the 10 particle m^{-2} shower density group should be free from multiple hit effects, but it lacks precision and could be consistent with Bassi, Clark, and Rossi's result.

Since Jelley and Whitehouse find $0 \cdot 6$ per cent. of shower particles with delays between 3 and 70 cμsec, and it is known that about 1 per cent. of shower particles are penetrating μ-mesons, it appears, when their results are combined with the present results, that the production of low energy mesons in air showers at low altitudes is about as great as the production of high residual energy ones at all altitudes. This is equivalent to an attempt at deducing the vertical distribution of meson production from measurements on residual ranges and delays alone. It would be valid only if all mesons travelled parallel to the shower axis and did not decay. In practice mesons produced at high altitude with low enough energy to have a large time lag and small residual range at sea-level, may diffuse towards the outer extremities of the shower or decay before reaching sea-level. Then an apparatus such as the present one, which is biased towards detecting showers near the core, might be expected to receive most of its low energy mesons from low altitudes. A false impression of the production at high altitudes would be obtained since only the high energy mesons would be received from those altitudes. It therefore seems desirable to locate the shower core in any such experiment. It might be found that the highly delayed particles become more penetrating as the distance from the core increases provided sufficient of those produced at high altitude survive.

V. Conclusions

In extensive air showers of median density 28 particles m^{-2} at sea-level, between 3 and 9 in 10^4 shower particles are delayed by more than 5 cμsec with respect to the electrons, and are able to penetrate at least 15 cm of lead. When this is combined with the results obtained by Jelley and Whitehouse it appears that 81–94 per cent. of the delayed particles in air showers are absorbed by 15 cm of lead. As the delayed particles are likely to be mostly μ-mesons, it follows that at least half of the delayed particles detected without absorbers were produced below an altitude of 0·8 km.

In extensive air showers of median density 28 particles m^{-2}, μ-mesons having residual ranges between 15 and 30 cm of lead have a mean height of production below 250 m.

In a total of 782 observed showers two detected μ-mesons were both significantly delayed and brought to rest in 25–30 cm of lead. Their most probable heights of production were calculated to be $1\cdot0^{+0\cdot7}_{-0\cdot4}$ km and $4\cdot7^{+4\cdot5}_{-2\cdot2}$ km.

One penetrating delayed proton was observed but it is likely that most particles in air showers delayed by more than a few cμsec are μ-mesons.

It is likely that path differences rather than velocity differences caused some of the delays observed.

VI. Acknowledgments

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VII. References

Bassi, P., Clark, G., and Rossi, B. (1953).—*Phys. Rev.* **92** : 441.
Greisen, K. (1949).—*Phys. Rev.* **75** : 1071.
Jelley, J. V., and Whitehouse, W. J. (1953).—*Proc. Phys. Soc. Lond.* A **66** : 454.
McCusker, C. B. A., Ritson, D. M., and Nevin, T. E. (1950).—*Nature* **166** : 400.
Mezzetti, L., Pancini, E., and Stoppini, G. (1951).—*Phys. Rev.* **81** : 629.
Officer, V. C. (1951).—*Aust. J. Sci. Res.* A **4** : 526.
Officer, V. C., and Eccles, P. J. (1954).—*Proc. Phys. Soc. Lond.* (in press).
Singer, S. F. (1951).—*Phys. Rev.* **81** : 579.