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## Transition Curves for Electron and Photon Produced Showers

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An investigation has been made of the air-to-lead transition curves for electron and photon initiated showers. The results show that the maximum of the curve for photon-produced showers is displaced to the right with respect to the maximum for electron produced showers by a thickness of about 3 mm of lead. This is in agreement with the prediction of shower theory. It was also confirmed that the maximum for large showers lies at a greater thickness than that for small showers. The occurrence of a "second maximum" in the air-to-lead transition curve was checked and a negative result obtained.

### INTRODUCTION

SINCE the discovery of cosmic-ray showers, the transition curve produced by these showers has been the subject of a large number of theoretical and experimental investigations. The best explanation of this curve at the present time is the cascade or multiplicative theory of showers as developed by several authors.[1] Although this theory has been confirmed in many respects, there are yet points where the consequences of the theory have not been conclusively tested and where various observers have obtained contradictory results. More experimental work appears to be desirable at these places.

The purpose of the present experiment was to investigate (a) the position of the maxima for showers initiated by photons and electrons, (b) the position of the maxima for showers of different sizes and (c) the existence of the so-called second maximum. The latter item is particularly important in connection with the cascade theory since its existence would indicate the existence of shower processes different from those predicted by this theory.

### EXPERIMENTAL ARRANGEMENT

The experimental arrangement for investigating the first two points is shown in Fig. 1. The G-M counters employed were of the argon-air filled type having an average efficiency of about 97 percent. Counters designated by the same number are connected in parallel. The lead scatterer (*S*) was placed below counter group 5 so that all particles which produced showers in the scatterer would pass through this counter group. Lead walls 10 cm thick were placed at both sides of the arrangement to reduce the background count due to air showers. The effect of the lead shielding in eliminating the counts due to air showers was reduced to some extent by the production of knock-on showers by mesotrons in the lead itself.

Since it was desired to record various coinci-

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[1] J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937); H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937); L. Landau and G. Rumer, Proc. Roy. Soc. **A166**, 213 (1938); H. Snyder, Phys. Rev. **53**, 960 (1938); R. Serber, Phys. Rev. **54**, 317 (1938).

dence combinations simultaneously, a selective, multiple coincidence circuit[2] was developed for this purpose. Each of the counters (or counter groups) 1, 2, 3, 4, and 5 were coupled to the grid of a corresponding vacuum tube. The plates of the tubes coupled to 1, 2, and 3 were tied together in the usual manner and received their potential through a 50,000-ohm resistance $R$, while the plates of the tubes coupled to 4 and 5 were connected to $R$ through extra resistances of

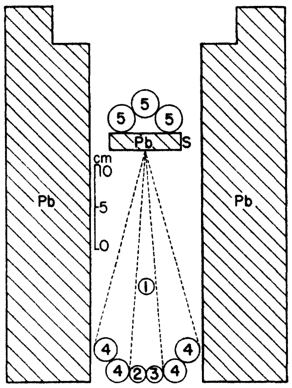


FIG. 1. Experimental arrangement for investigating the Rossi transition curve at thin thicknesses.

175,000 and 100,000 ohms, respectively. Pulses of various sizes were produced at the low potential side of $R$ by different combinations of coincidences. The largest pulse produced was that due to a discharge of all the counters 12345 which will be designated as $N_{12345}$. The next largest pulse was produced by a discharge of only counters 1235 which will be represented by $N_{1235-4}$, and successively smaller pulses were produced by discharges of only counters 1234 and only 123 designated as $N_{1234-5}$ and $N_{123-45}$, respectively. These different sized pulses were separated by feeding them onto the grids of four tubes differing in grid bias by the appropriate amounts and finally recorded by feeding the output of these tubes into four multi-vibrator recording circuits. Pulses due to coincidence combinations other than those mentioned above are very small and could easily be rejected.

It is evident from Fig. 1 that a coincidence $N_{123-45}$ or $N_{1235-4}$ requires a minimum of two particles, while a coincidence $N_{1234-5}$ or $N_{12345}$ requires a minimum of three particles. In general, the average size of shower discharging only counters 123 will be smaller than that discharging 1234 and therefore, $N_{123-45}$ or $N_{1235-4}$ may be called small showers and $N_{1234-5}$ or $N_{12345}$ large showers. The above shower types recorded with similar arrangements have been also referred to as "small angle" and "large angle" showers. This nomenclature is rather misleading, since except at small thicknesses the average angular distribution is the same for all showers from a given material. Since the density of shower particles is greatest at the center of a shower and decreases toward the edges, it is clear that as the number of shower particles is increased the particle density at the edges is also increased. Therefore, the probability that a counter placed at the edge of a shower will be discharged depends upon the number of particles in the shower rather than upon any "angle."

Counter group 5 was used to distinguish between electron and photon initiated showers. Apart from a small inefficiency of the counters, an electron would almost always discharge this group while a photon would not unless the Compton effect or pair production occurred in the walls of the counter. The probability of either of these events is small, but if either of the above processes occur in the upper walls of the counter the event would be recorded as an electron produced shower. Another disturbing effect would be the simultaneous arrival of electrons and photons, but this is a rare event.

With the above methods of distinguishing showers, the following types of showers were recorded: large ($N_{12345}$) and small ($N_{1235-4}$) electron initiated showers and large ($N_{1234-5}$) and small ($N_{123-45}$) photon initiated showers. Observations were made every twenty-four hours at

TABLE I. Results of the determination of transition curves for various shower types.

| Thickness of Lead | Counts per Hour $N_{12345}$ | $N_{1235-4}$ | $N_{1234-5}$ | $N_{123-45}$ |
|---|---|---|---|---|
| 0.000 cm | 0.0 | 0.0 | 0.0 | 0.0 |
| 0.318 | 0.30±0.02 | 0.28±0.03 | 0.26±0.02 | 0.55±0.03 |
| 0.635 | 0.55±0.02 | 0.50±0.03 | 0.56±0.02 | 1.00±0.03 |
| 0.953 | 0.78±0.03 | 0.46±0.04 | 0.91±0.03 | 1.38±0.04 |
| 1.270 | 0.94±0.04 | 0.40±0.04 | 1.29±0.03 | 1.34±0.04 |
| 1.588 | 0.99±0.04 | 0.31±0.03 | 1.59±0.04 | 1.12±0.04 |
| 1.905 | 0.94±0.03 | 0.28±0.03 | 1.71±0.04 | 0.68±0.03 |
| 2.222 | 0.87±0.03 | 0.22±0.02 | 1.61±0.03 | 0.43±0.02 |
| 2.540 | 0.79±0.03 | 0.15±0.02 | 1.51±0.02 | 0.34±0.02 |

[2] L. Janossy and B. Rossi, Proc. Roy. Soc. **A175**, 88 (1940).

thickness intervals of 0.318 cm up to a maximum thickness of 2.54 cm of lead.

The experimental arrangement for investigating the second maximum was identical to that employed by Bothe and Schmeiser[3] in their investigation of the second maximum. This particular arrangement was used since the above investigators have observed the most pronounced second maximum. Triple coincidences were observed as the thickness of the lead was varied at 4 cm intervals from 12 to 24 cm. Only the latter part of the transition curve was investigated since this range is sufficient to ascertain if any second maximum exists.

## RESULTS

The data obtained in the first experiment are shown in Table I in which each reading represents an average of about 1000 coincidences observed over a period of about five months. The counting rate obtained with no lead for each shower type has been subtracted from the observed counting rate. This rate was different for each shower type but the average was about 2 counts per hour. The standard errors are given.

The transition curves produced by the total electron ($N_{12345}+N_{1235-4}$) and total photon ($N_{1234-5}+N_{123-45}$) showers are shown in Fig. 2. These curves bring out the significant fact that the maximum for photon initiated showers is shifted further to the right by 0.25 to 0.3 cm as compared to the electron initiated shower curve. This shift may be determined more accurately if each of these two curves is subdivided into transition curves for small and large showers such as has been done in Figs. 3 and 4, respectively. In these curves the errors are less and the maxima are better defined. The photon and electron maxima occur at 1.1 and 0.75 cm in Fig. 3 and at 1.9 and 1.6 cm in Fig. 4, showing a difference between the two maxima of 0.35 and 0.3 cm, respectively. A comparison of these curves also shows that the maximum for large showers occurs further to the right than that for small showers.

The data from the second experiment are given in Table II. It is evident that no second maximum is indicated but merely a straight line with perhaps a slight negative slope.

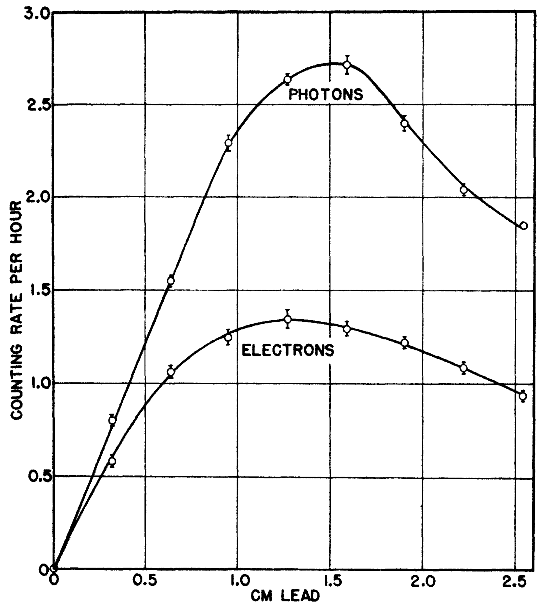


Fig. 2. Transition curves for total electron and total photon initiated showers.

## DISCUSSION

The probability of recording a shower increases when the average number of particles is increased and it is safe to assume that the maximum coincidence rate is recorded when the average number of particles is a maximum. Now, the thickness of scatterer at which an electron of energy $E_0$ and a photon of energy $W_0$ produce a maximum number of particles has been calculated[4] from the multiplicative theory to be

$$T(E_0)=1.01[\log (E_0/\epsilon)-1]$$

for an electron, and

$$T(W_0)=1.01[\log (W_0/\epsilon)-\tfrac{1}{2}]$$

for a photon where $\epsilon$ is the critical energy. If ionization losses are neglected it can be shown[4] that the energy spectrum of photons and electrons is the same. Therefore, it follows from the above formulae that the maximum number of particles in a shower initiated by a photon should occur at a thickness of one-half a radiation length

[3] K. Schmeiser and W. Bothe, Ann. d. Physik **32**, 161 (1938).

[4] B. Rossi and K. Greisen, Rev. Mod. Phys. **13**, 240 (1941).

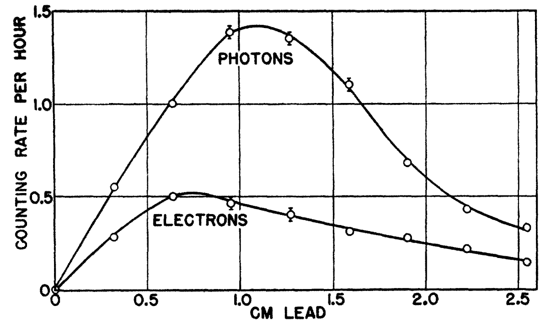


FIG. 3. Transition curves of small showers produced by electrons and photons.

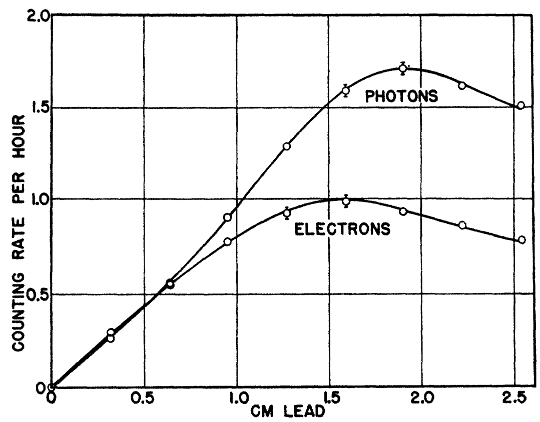


FIG. 4. Transition curves of large showers produced by electrons and photons.

greater than that for a shower initiated by an electron. This amounts to 0.3 cm in the case of lead. The experimental values as presented in the previous section are in good agreement with this figure.

Previous work on the transition curves produced by electrons and photons has been done by a few investigators without reaching any definite conclusion as to the positions of the maxima. Woodward's[5] results indicate a slight shift, but his experimental arrangement does not separate the two shower types sufficiently to verify the shift. The curves obtained by Starr[6] and by Regener[7] contain too few points in the region of the maxima to show any shift.

A number of investigators[8] have confirmed the theoretical expectation that the maximum for large showers should occur at greater thicknesses than that for small showers. The present investigation confirms these results by showing the maxima for small and large showers to be at 1.0 and 1.8 cm, respectively. Arley[9] has calculated the maximum for showers produced in lead by two or more particles to be at 1.3 cm and that for three or more particles at 1.6 cm. However, since the geometrical arrangement plays such a large part here, it is difficult to compare these values with the experimental ones.

The occurrence of a second maximum has continued to be a subject for investigation since it was first reported by Ackemann[10] and Hummel[11] in 1934. The continued interest in this subject is due to the facts that its occurrence is very important in regard to shower theory and that some investigators[12] have confirmed its existence while others[13] have not. Bothe and Schmeiser found the second maximum to be almost as high as the first in their experiments on narrow showers, but the present experiment with an identical arrangement fails to confirm this result.

TABLE II. Results of the investigation of the occurrence of a second maximum.

| Thickness of Lead | Total Number of Counts Observed | Triple Coincidences per Hour |
|---|---|---|
| 12 cm | 4000 | $7.0 \pm 0.1$ |
| 16 | 5000 | $6.9 \pm 0.1$ |
| 20 | 5000 | $6.9 \pm 0.1$ |
| 24 | 2500 | $6.9 \pm 0.1$ |

[5] R. H. Woodward, Phys. Rev. **49**, 711 (1935).
[6] M. A. Starr, Phys. Rev. **53**, 6 (1938).
[7] V. H. Regener, Ric. Scient. **18**, 66 (1940).
[8] R. B. Brode and M. A. Starr, Phys. Rev. **51**, 1006 (1937); D. K. Froman and J. C. Stearns, Phys. Rev. **52**, 382 (1937); R. T. Young, Jr., Phys. Rev. **52**, 559 (1937); M. A. Starr, Phys. Rev. **53**, 6 (1938).
[9] N. Arley, Proc. Roy. Soc. **A168**, 519 (1938).
[10] M. Ackemann, Naturwiss. **22**, 169 (1934).
[11] J. N. Hummel, Naturwiss. **22**, 170 (1934).
[12] A. Drigo, Ric. Scient. **5**, 88 (1934); H. Kulenkampff, Physik. Zeits. **36**, 785 (1935); H. Maass, Ann. d. Physik **27**, 507 (1936); J. A. Priebsch, Akad. Wiss. Wien. Ber. **145**, 101 (1936); J. Clay, A. van Gemmert, and J. T. Wiersma, Physica **3**, 627 (1936); R. H. Woodward, Phys. Rev. **49**, 711 (1936); J. Clay and K. H. J. Jonker, Rev. Mod. Phys. **11**, 287 (1939); W. F. G. Swann and W. F. Ramsey, Phys. Rev. **58**, 477 (1940); P. J. G. De Vos, Nature **145** 387 (1940).
[13] A. Schwegler, Zeits. f. Physik **101**, 93 (1936); K. Z. Morgan and W. M. Nielsen, Phys. Rev. **52**, 564 (1937); P. Auger, R. Maze, P. Ehrenfest, and A. Freon, J. de phys. et rad. **10**, 1 (1939); B. Rossi and L. Janossy, Rev. Mod. Phys. **11**, 281 (1939); P. Auger and T. Grivet, Rev. Mod. Phys. **11**, 232 (1939); G. O. Altmann, H. N. Walker, and V. F. Hess, Phys. Rev. **58**, 1011 (1940); L. Janossy, M. McCaig, and E. P. George, in print; W. M. Nielsen, J. E. Morgan, and K. Z. Morgan, Phys. Rev. **55**, 995 (1939).

This is in agreement with the findings of Altmann, Walker, and Hess[13] who have carried out an experiment similar to the one described here.

A final point may be brought out from the fact that the counting rate is practically the same at 12 as at 24 cm of lead. In consideration of the error in these readings, one can conclude that the maximum decrease in this counting rate could be only 3 to 4 percent, while the total decrease in the number of mesotrons brought about by 12 cm of lead is about 8 percent.[14] This difference may be explained by considering that only mesotrons of high energy are capable of producing knock-on showers. By considering the experimentally determined mesotron energy spectrum, Lovell[15] has calculated that the probability of observing knock-on showers is highest when the energy of the mesotron lies between 3 and $6\times 10^9$ ev. If $5\times 10^9$ ev is taken as the most probable mesotron energy for observing a knock-on shower with the present experimental arrangement, it can be shown that the energy spectrum above $5\times 10^9$ ev is decreased by only 3 percent by 12 cm of lead. The slight decrease of this energy spectrum compared with the slight decrease in the counting rate indicates that only mesotrons above energies of the order of $5\times 10^9$ ev produce knock-on showers.

In conclusion, the author wishes to thank especially Professor J. C. Stearns for his suggestion and direction of the experiment and also Professor D. K. Froman for helpful comments. To Professor Bruno Rossi and Mr. Kenneth Greisen of Cornell University the author is deeply grateful for valuable discussions on the interpretation of the results.

[14] B. Rossi and D. Hall, Phys. Rev. **59**, 223 (1941).
[15] A. C. B. Lovell, Proc. Roy. Soc. **A172**, 568 (1939).

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# Frequency of Proton and Alpha-Tracks in Cosmic-Ray "Stars"

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To obtain data concerning the multiple nuclear disintegrations produced by the cosmic radiation, special photographic plates were left on Mt. Evans for nearly eight months. From a statistical investigation of 365 tracks in 142 cosmic-ray "stars" found in one of these emulsions, it is estimated that more than 90 percent of the tracks were produced by protons. Most of the remaining star tracks are probably due to alpha-particles of energy less than 9 Mev.

## INTRODUCTION

EVIDENCE of multiple nuclear disintegrations associated with the cosmic radiation has been provided by cloud chambers,[1] by photographic emulsions,[2] and indirectly by proportional counters.[3]

Of 20,500 counter-tripped cloud-chamber photographs of cosmic rays obtained by Brode and Starr[1a] at sea level, ten showed nuclear disintegrations produced by the cosmic radiation with the emission of heavy[4] particles. Even at an altitude of 4300 m[1b] only a few such disintegrations were observed in thousands of photographs. Because of the rare occurrence of these events, the continuously sensitive photographic emulsion has proved a useful tool in their investigation.

In the photographic emulsion a multiple nuclear disintegration produces a "fork," or group of microscopic tracks emanating from a common center. Each track consists of a row of discrete silver grains spaced several microns apart, the spacing being greater for protons than for alpha-

[1] (a) R. B. Brode and M. A. Starr, Phys. Rev. **53**, 3 (1938); (b) C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936); (c) J. Crussard and L. Leprince Ringuet, J. de phys. et rad. [7] **8**, 216 (1937).
[2] References 6–10 are to photographic emulsion studies of cosmic rays. Résumé and bibliography, M. M. Shapiro, Rev. Mod. Phys. **13**, 58 (1941).
[3] S. A. Korff, Phys. Rev. **59**, 949 (1941).
[4] The word "heavy" will be used here to describe particles at least as massive as protons.