Internally converted gamma-rays, associated with the short-lived activity, are found to have energies of 133.7, 328.9, 489.6, and 623.6 kev.

It can be observed that the sum of the energies of the first and third gamma-rays is almost identical to that of the highest value. An analysis of the decay curve indicates that certain longer lived activities are present. The correct solution must await further aging of the specimen.

By lead absorption there appears to be a high energy gamma-ray at about 2.1 Mev.

RHENIUM

Rhenium exists as two stable isotopes, of mass 185 (38.2 percent) and mass 187 (61.8 percent). Neutron capture should produce Re 186 reported[6] as having a half-life of 90 hours and Re 188 with a half-life of 18 hours. The pile irradiated specimen was exceedingly active, indicating a large capture cross section particularly for Re 185. A specimen with minimum usable mass gave good spectrograms, with an exposure of 20 minutes instead of several days as required for many other elements.

[6] K. Fajans and W. Sullivan, Phys. Rev. **58**, 276 (1940).

An analysis of the half-life curve showed the principle decay to have a 91-hour half-life, together with an additional initial activity whose half-life is determined as approximately 16 hours.

Both emitters yield conversion electrons from which the gamma-rays are evaluated. A single converted gamma-ray of energy 153.6 kev is observed for the shorter half-life. For the 91-hour activity gamma-rays of energy 122.7, 135.8, and possibly 137.5 kev are found. In each case the $K-L-M$ electron peaks are observed and the 'L' line appears in the 91-hour activity stronger than the 'K'. An additional gamma-ray of energy 0.64 Mev is indicated by absorption in lead. The upper limit of the beta-spectrum for the 91-hour activity appears by absorption in aluminum to be at 0.70 Mev.

The values of the energies and half-lives observed in this investigation are shown collectively in Table I. These studies were made possible by the support of the Atomic Energy Commission and the Office of Naval Research.

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Cosmic-Ray Bursts at Sea Level and under Thirty Meters of Clay

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Cosmic-ray bursts have been investigated by means of ionization chambers made of Duralumin, of volume 1.15 liter and wall thickness 12 mm, filled with argon to pressures of about 82 atmos. at 0°C. The bursts were registered with recording electrometers. The experiments were carried out in a hut with a thin roof at sea level and in an underground station under 30 meters of clay. At both levels runs were made with the chambers unshielded and also with sheets of aluminium (up to 33 cm) and of lead (up to 18 cm) placed above them. In all, about 3000 hours at the underground station and 1000 hours at sea level were successfully recorded. The results obtained underground are the first systematic investigation concerning bursts observed far below sea level. The air-lead transition curves there show a flat maximum which occurs at a greater thickness of lead than that observed at sea level.

1. INTRODUCTION

THE energy of the ionizing charged part of the cosmic radiation can be measured directly and individually in a strong electromagnetic field with a cloud chamber, or indirectly and integrally, from the total energy lost in

* This paper has been condensed by H. Carmichael, without significant changes of wording, from a paper published by C. N. Chou, under the same title, in *Collected Papers* (College of Science and Engineering, National University of Amoy, China, 1943), Vol. 1, pp. 1–36. It has been submitted for publication in The Physical Review in the belief that experimental results are of considerable interest. The experimental data has been replotted from the original tables. Further discussion of the results will be found in the following paper. Two of the experimental curves were previously published in a short note: H. Carmichael and C. N. Chou, Nature **144**, 325 (1939).

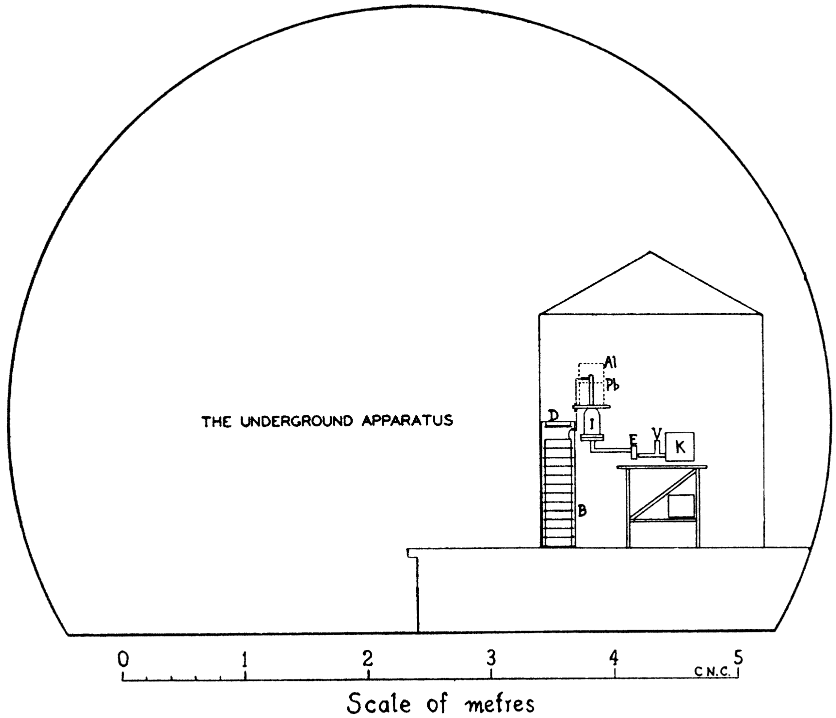


FIG. 1. The tube-station apparatus.

ionization, by observations carried out at different latitudes, making use of the selective effect of the earth's magnetic field. The energy limit reached by both these types of measurements is of the order of 10^{10} ev for singly charged particles of electronic mass. To get information about the behavior of the more energetic rays one has to resort to the study of the production of showers and bursts, which are secondary effects observed only with cosmic rays and are phenomena connected with the sudden release of a large amount of energy within a very short time initiated by a single primary. If our present theories[1–11] are correct, as seems probable, we have been able, by this means, to come to know the behavior of singly charged particles of electronic mass of energy up to the order of 10^{15} or 10^{16} ev.

While many experiments concerning Hoffmann[12] bursts at sea level and at high altitudes have been carried out under different conditions, so far experimental data concerning bursts under sea level are extremely meager.[13–15] Indeed no proper experiments specially designed for the investigation of bursts at great depths have yet been published.

In the present paper are reported experimental results concerning bursts at sea level and under thirty meters of clay.

2. APPARATUS

The sea-level experiments were made in a hut at Cambridge, England. The roof of the hut was of sheet iron about 1 mm thick and the ionization chamber was 110 cm below the roof and 90 cm from three sides of the ordinary brick wall. This apparatus was about 110 cm above sea level and

1 N. Arley, Proc. Roy. Soc. **A168**, 519 (1938).
2 H. J. Bhabha, H. Carmichael, and C. N. Chou, Proc. Ind. Acad. Sci. **A175**, 518 (1940).
3 H. J. Bhabha and W. Heitler, Proc. Roy. Soc. **A159**, 432 (1937).
4 F. Booth and A. H. Wilson, Proc. Roy. Soc. **A175**, 518 (1940).
5 J. F. Carlson and J. R. Oppenheimer, Phys. Rev. **51**, 220 (1937).
6 H. Euler, Zeits. f. Physik **110**, 450 (1938).
7 H. Euler, Zeits. f. Physik **110**, 692 (1938).
8 H. Euler, Zeits. f. Physik **116**, 73 (1940).
9 H. Euler and W. Heisenberg, Ergeb. d. exakt Naturwiss. **17**, 1 (1938).
10 L. Landau and G. Rumer, Proc. Roy. Soc. **A166**, 213 (1938).
11 H. S. W. Massey and H. C. Corben, Proc. Camb. Phil. Soc. **35**, 463 (1939).
12 G. Hoffmann, Ann. Physik **82**, 413 (1927).
13 F. Weischedel, Zeits. f. Physik **36**, 796 (1935).
14 F. Weischedel, Zeits. f. Physik **101**, 732 (1936).
15 Clay, Hooft, Dey, and Wiersma, Physica **4**, 121 (1937).

will be referred to as the sea-level apparatus. The underground experiments were carried out in a similar hut situated on a disused platform in the Holborn Underground Station, London. Above the platform were strata of different kinds of clay 30.8 m thick, the mean specific gravity of which was about two. Figure 1** gives the position of the ionization chamber in the hut. This apparatus will be referred to as the underground apparatus.

The apparatus used was almost exactly the same in both locations. A diagram of the ionization chamber, which was designed by Dr. H. Carmichael, is given in Fig. 2. The chamber was made of Duralumin 1.2 cm thick. The vertical cylindrical aluminium electrode B was connected to an electrometer and also to a small calibrating condenser and a high resistance leak. The chamber potential was carried on the aluminium electrode A which was mounted concentrically with the earthed wall of the chamber. The collecting volume was about 1150 cc. Two such chambers (No. B and No. C) were used at sea level, and one (No. A) underground. They were filled with commercial oxygen-free argon to pressures of 88 atmos. (No. A), 94 atmos. (No. B), and 87 atmos. (No. C) at 20°C. The chamber potential was about 1500-volts negative. The maximum time of collection for a positively charged ion traveling across the chamber was calculated to be less than 0.4 second.

The ionization was measured by an electrometer[16–18] which has been found to be specially suitable for the recording of bursts of all sizes. It had a gold-sputtered quartz fiber about 3 cm long and 10^{-4} cm in diameter. The air pressure in the electrometer, which for critical damping of the fiber was of the order of 0.05 mm mercury, was kept practically constant by connection of the electrometer to a 2-liter bottle. The complete response of the fiber to a sudden change of potential took approximately 0.5 second.

For continuous photographic registration of the position of the fiber, a camera with a cylindrical lens was used. The camera was driven by an induction motor to move a 16-mm unperforated cine-film at a uniform slow speed. The fiber was illuminated so that it shone by diffracted light against a dark background. The film speed was about 0.05 mm per sec. A time scale was recorded on the film.

Immediately above the ionization chamber was a wooden platform, of size about 30 cm×30 cm and about 2 cm thick, used as a support for different materials. This platform remained in position when all the experiments were being carried out.

The ionization chamber potential of 1500 volts was obtained from twelve dry batteries of 125 volts each. The batteries were piled up vertically and were insulated from one another by paraffin papers. No smoothing condenser was used and

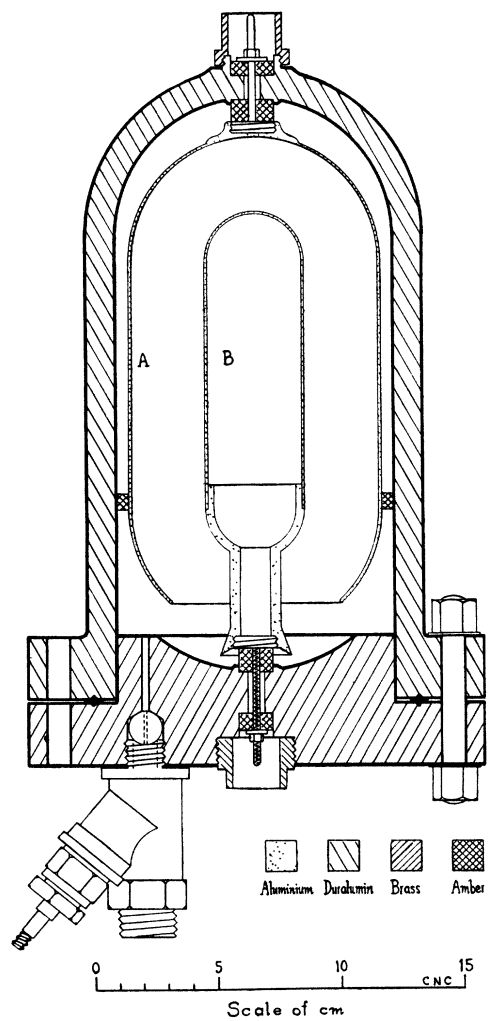


FIG. 2. The ionization chamber.

** See also Fig. 2 in the following paper.
[16] H. Carmichael, Proc. Phys. Soc. **44**, 400 (1932).
[17] H. Carmichael, Proc. Phys. Soc. **46**, 169 (1934).
[18] H. Carmichael, Proc. Roy. Soc. **A154**, 223 (1936).

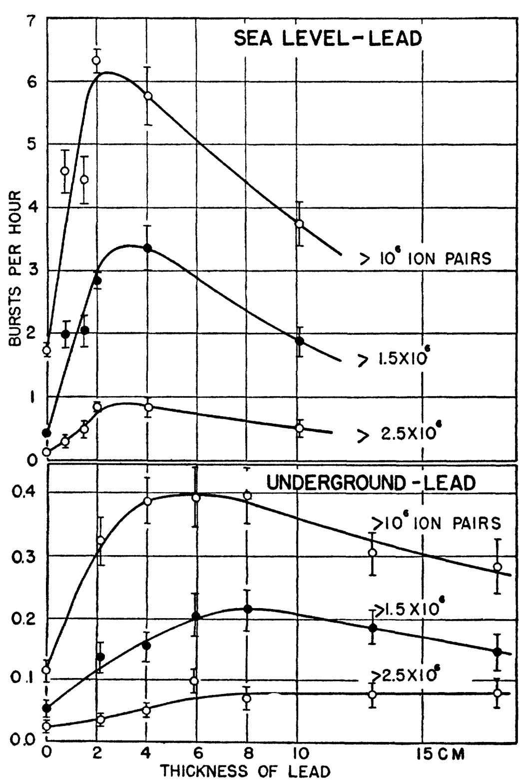
the general behavior was found to be very satisfactory.

A small electromagnet was used to operate a switch with platinum contacts for earthing the fiber, or applying a definite known voltage to it in testing the sensitivity of the electrometer. The charge calibration could be made by applying a known voltage to the calibrating condenser, which consisted of a circular brass disk with a guard ring. The calibrating condenser in each set of the apparatus was compared directly with a standard variable cylindrical condenser. Both voltage and charge calibrations were registered frequently on the film.

The high resistance leak, a lacquered graphite-on-Pyrex resistance,[19] gave a half-time of about 10 seconds. Its value was between 10^{11} and 10^{12} ohms.

Experiments were performed with lead sheets and aluminium plates of size 20 cm×20 cm of different thicknesses. A short run was made at sea level with 2.05 cm of lead 34.5 cm higher up than the normal position. Unshielded runs were frequently made, and experiments with each thickness of material were made in at least two separate runs.

The apparatus was left running day and night. The sea-level apparatus was examined once a day to make the required adjustments and calibrations. The underground apparatus was left unattended for three or four days. To examine this



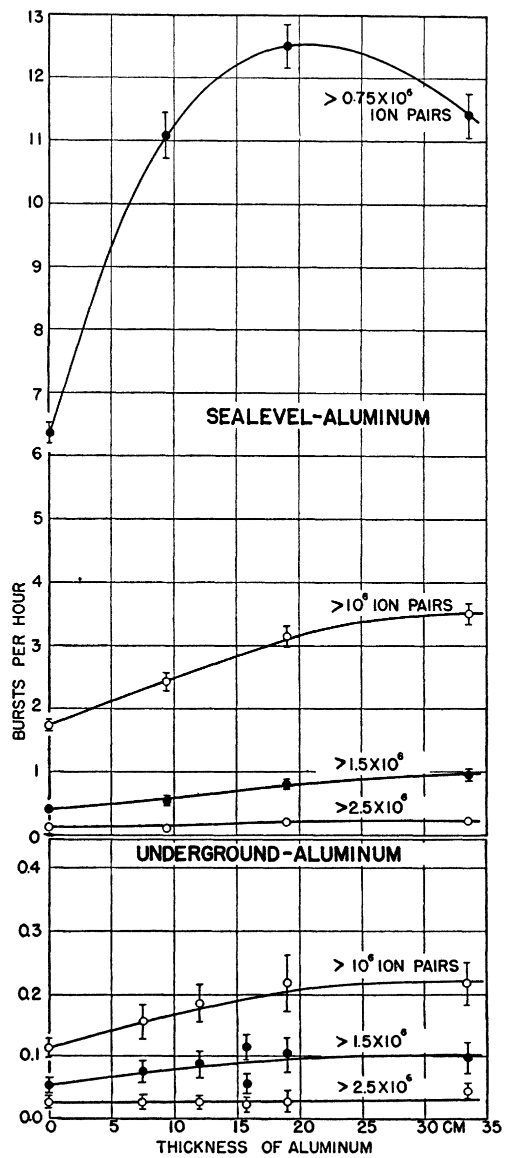


FIG. 3. Effect of shields.

[19] L. F. Curtiss, Rev. Sci. Inst. 4, 679 (1933).

last mentioned apparatus the writer went to London from Cambridge regularly twice a week for more than one year (1937 winter to 1939 spring).

Altogether 2900 hours of successful recording underground and 330 hours for chamber No. *B* and 650 hours for chamber No. *C* at sea level were obtained.

3. EXPERIMENTAL RESULTS

The personal errors in counting the bursts are estimated to be not high. No barometric effect correction is made. The results are given in the form of transition curves and integral number-size curves in Figs. 3 and 4. The errors indicated in Fig. 3 are the standard deviations, and the errors in Fig. 4 may be estimated from the fact that the last experimental point in each curve at the low frequency end represents only one burst, the largest which occurred during the run.

The sizes of the bursts are expressed in terms of the measured number of ion pairs. An estimate of the corresponding number of thinly ionizing cosmic-ray particles involved may be made by

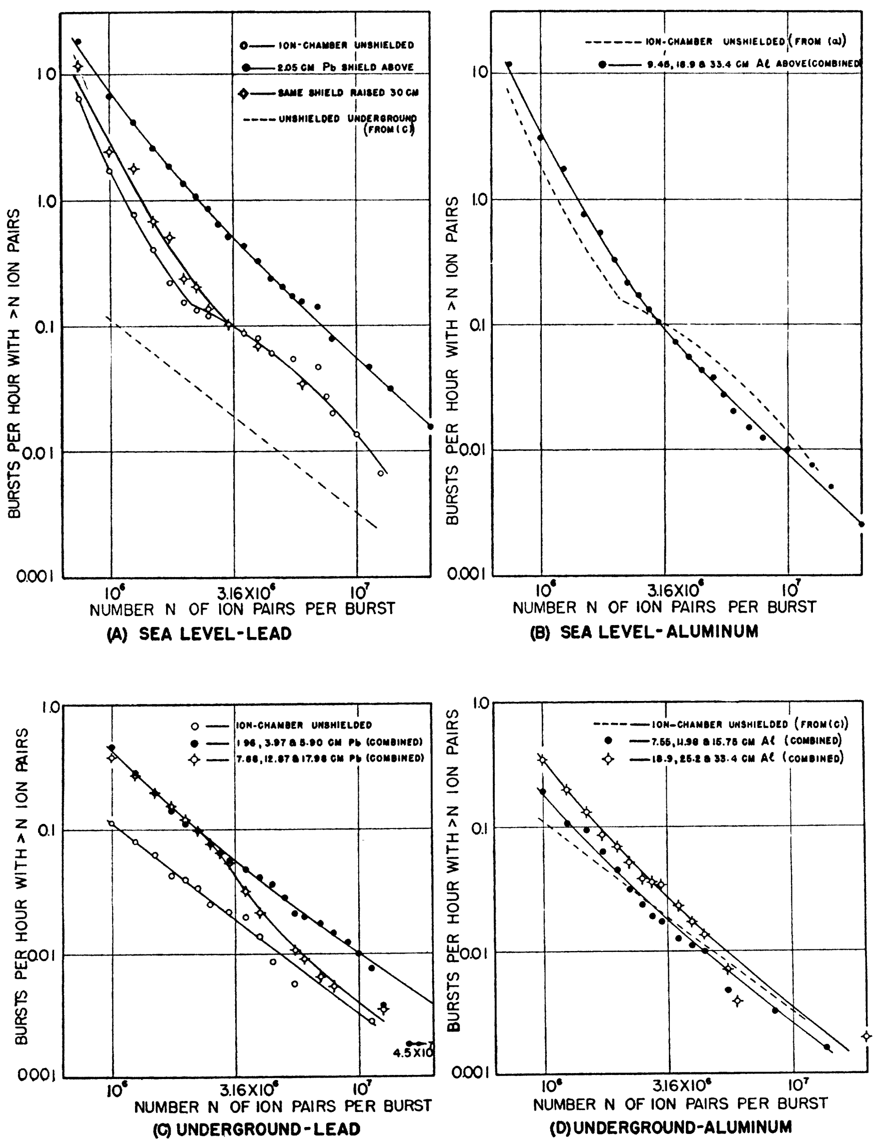


FIG. 4. Integral size frequency relations.

assuming that each ray produces 80 ion pairs per cm in argon at atmospheric pressure and that the average path length in the chamber, of a ray (directed near to the vertical), is 15 cm: hence each ray will produce on the average 10^5 ion pairs, assuming negligible recombination in argon at 82 atmos. pressure.

3.1 Transition Curves

The air-lead transition curves at sea level (Fig. 3) confirm the results of earlier authors.[18, 20–23] The displacement of the maximum toward greater thicknesses with bursts of greater sizes can be seen fairly clearly.

In the case of aluminium the transition curves at sea level (Fig. 3) show no rapid linear increase with thickness like that reported by Nie.[24]

No sharp maxima are observed for the air-lead transition curves underground (Fig. 3). However, the displacement of the flat maximum toward small thicknesses with smaller sizes of bursts is probably real.

Some of the experimental points of the air-aluminium transition curves underground (Fig. 3) disperse rather far away from the smooth curves. However, that there is a definite appreciable increase of the number of bursts with increasing thicknesses seems to be certain.

3.2 Number-Size Distributions

A noticeable feature of the integral number-size distribution curves shown in Fig. 4 is that several of them cannot be represented by a single straight line, i.e., not by a simple power law of the form[25]

$$F(N)=A/N^s, \qquad (1)$$

where $F(N)$ denotes the number of bursts greater than N ion pairs and A and s are constants for a particular material. (This was pointed out by Carmichael and Chou in 1939.*)

The number-size curves of the bursts from lead always show more bursts than the corresponding unshielded runs. In the case of aluminium, both at sea level and underground, the number of big bursts is practically the same as in the corresponding unshielded runs, although for all thicknesses there is a definite increase in the number of small bursts. The value of the index s in formula (1) is higher in the case of aluminium than in lead, in the range of small bursts in agreement with the results of Montgomery and Montgomery.[25] The divergence between the curves with and without lead, in Fig. 4A, confirms similar results of Montgomery and Montgomery.[26] When the lead sheets are in the elevated position*** (Fig. 4A) there is a general decrease in the number of bursts of all sizes and the curve becomes more similar to that of the unshielded run.

3.3 Depth-Intensity Relations

The value of the vertical intensity at sea level was from 17 to 19 times that in the underground station, according to the measurements of Follet and Crawshaw,[27] Crawshaw,[28] and Janossy,[29] who all worked on the same platform of the same underground tunnel as the writer.

Bursts from lead, at the maxima of the transition curves of Fig. 3, appear to be about 15 times more frequent at sea level than in the underground station. On the other hand, when the chambers are unshielded, bursts of size greater than 3×10^6 ion pairs† are little more than 5 times more frequent (Fig. 4A) at sea level than underground.

These results may be compared with those concerning showers,[27, 28, 30–36] the number of which,

[20] J. K. Bøggild, dissertation, Copenhagen (1937).
[21] W. P. Jesse, Phys. Rev. **53**, 691 (1938).
[22] H. Nie, Zeits. f. Physik **99**, 453 (1936).
[23] R. T. Young, Phys. Rev. **52**, 559 (1937).
[24] H. Nie, Zeits. f. Physik **99**, 776 (1936).
[25] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **48**, 969 (1935).
[26] C. G. Montgomery and D. D. Montgomery, Phys. Rev. **56**, 640 (1940).
*** It is unfortunate that facilities were not available to have conducted these experiments with hemispherical shielding. The experiment with lead in the elevated position shows that bursts from the more distant portions of the small shields used tended to miss the chamber altogether. H.C.
[27] D. H. Follet and J. D. Crawshaw, Proc. Roy. Soc. **A155**, 546 (1936).
[28] J. D. Crawshaw, Proc. Phys. Soc. **50**, 783 (1938).
[29] L. Janossy, Proc. Roy. Soc. **A167**, 499 (1938).
† Because of the steeper part of the sea-level curve which does not appear to occur underground, comparison of the unshielded chambers for bursts of size smaller than 3×10^6 ion pairs would yield a larger ratio. In this connection see the following paper. H. C.
[30] P. Auger and T. Grivet, Rev. Mod. Phys. **11**, 232 (1939).
[31] J. Barnothy and M. Forro, Zeits. f. Physik **104**, 744 (1937).
[32] J. Clay and P. H. Clay, Physica **2**, 1042 (1935).
[33] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).

especially of the bigger ones, has been found to decrease less rapidly with depth than the vertical intensity.

4. DISCUSSION OF RESULTS

4.1 Unshielded Runs

An interpretation of the results observed in unshielded runs invoking the effect of air showers[37–43] was given by Carmichael and Chou,* and independently by Montgomery and Montgomery.[26] A detailed analysis has since been given by Euler.[8] The validity of the energy spectrum for world-space electrons,

$$H(E) = (\text{const.}/E^{1.8}), \qquad (2)$$

is established for the range 2.10^9 ev $< E < 3.10^{15}$ ev, where $H(E)$ denotes the frequency of electrons above energy E (see also reference 36). It may be remarked here that while Euler's interpretation of the branch of smaller bursts in the case of Carmichael's big chamber as due to cosmic-ray induced nuclear disintegrations seems to be satisfactory, the same interpretation for a small chamber (one of the chambers used in the experiments reported here) could not be true as the latter chamber was made of Duralumin instead of iron, and the pressure of argon was almost 90 atmospheres.††

4.2 Sea-Level Results

The bursts produced in lead at sea level up to medium thicknesses can be explained as bursts produced by electrons and photons falling upon the material sheets, according to cascade theory. The positions of the maxima of the transition curves, the displacement of these maxima toward bigger thicknesses with increasing size of the bursts, the widths of the maxima, and the slopes of the number-size curves are given correctly by the theory (see, however, Bethe[44] and Oppenheimer[45]) if one assumes the empirical spectrum of world-space electrons given by expression (2). The decay electrons of mesons are of low energies and contribute only negligibly.

The initial slope of the aluminium transition curve at sea level for bursts of medium size (for bursts of size greater than 10^6 ion pairs) is much the same as that of the air-lead transition curve when both curves are measured in the length units of the cascade theory. It is interesting to note that if the big bursts were caused by a mechanism connected with the nuclear mass, for example, the explosive type suggested by Heisenberg,[46, 47] one should expect far more big bursts to occur (in Al) than those observed.

4.3 Underground Results†††

The underground transition curves compare favourably with those concerning showers observed with counters.[27–30, 48] For example, the rate of occurrence of bursts underground can be compared with that of the showers measured by Janossy in the same underground tunnel. The effective area of the set of five counters used by Janossy[29] was about 300 sq. cm, and it required at least three rays to actuate his counters in the pentagonal disposition. He found 0.6 coincidence per hour when the counters were 3 meters below the roof of the tunnel and unshielded. The effective area of the ionization chamber was about 100 sq. cm: $\frac{1}{3}$ of that of Janossy's apparatus. Hence we would expect it to intercept on the average only one ray of each of the smallest showers measured by Janossy. If we extrapolate the lower curve in Fig. 4C to find the number of bursts of size greater than one ray (i.e., 10^5 ion

[34] T. Grivet-Meyer, Comptes Rendus Acad. Sci. (Paris) **206**, 833 (1938).
[35] W. H. Pickering, Phys. Rev. **52**, 1131 (1937).
[36] V. C. Wilson, Phys. Rev. **53**, 337 (1938).
[37] P. Auger, Comptes Rendus Acad. Sci. (Paris) **207**, 907 (1938).
[38] Auger, Ehrenfest, Maze, Daudin, Robley, and Freon, Rev. Mod. Phys. **11**, 288 (1939).
[39] P. Auger and R. Maze, Comptes Rendus Acad. Sci. (Paris) **207**, 228 (1938).
[40] P. Auger and R. Maze, Comptes Rendus Acad. Sci. (Paris) **207**, 671 (1938).
[41] Auger, Maze, Ehrenfest, Jr., and Freon, J. de phys. et rad. **10**, 39 (1939).
[42] P. Auger, R. Maze, and T. Grivet-Meyer, Comptes Rendus Acad. Sci. (Paris) **206**, 1721 (1938).
[43] L. Janossy and A. C. B. Lovell, Nature **142**, 716 (1938).
†† See, however, the fuller discussion in the following paper. H.C.

[44] H. A. Bethe, Phys. Rev. **57**, 1062 (1940).
[45] J. R. Oppenheimer, Rev. Mod. Phys. **11**, 264 (1939).
[46] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936).
[47] W. Heisenberg, Zeits. f. Physik **113**, 61 (1939).
††† A discussion of bursts produced underground by electrons knocked on by mesons, but not including bursts produced by gamma-radiation from mesons, has been given by Bhabha, Carmichael, and Chou (see reference 2). For a comprehensive account of bursts produced by mesons see Christy and Kusaka, Phys. Rev. **59**, 414 (1941). H.C.
[48] D. H. Follet, Proc. Phys. Soc. **51**, 585 (1939).

pairs) which would be observed, we find the number to be 0.65 per hour, which agrees satisfactorily with Janossy.‡

Subsequently, George[49] did some shower experiments in the same underground station as the writer, using four counters arranged in a square array with hemi-cylindrical sheets of different materials placed above them. In the case of the air-lead transition curves he found a reasonably sharp maximum at about 1 cm of lead, and the number of showers decreased but very slowly up to 22 cm of lead.

The air-aluminium transition curves observed underground agree qualitatively with the corresponding shower transition curves reported by Auger and Grivet.[30]

5. CONCLUSION

Summing up, although the possibility of some non-electromagnetic processes for the production of bursts observed here (from about 10 rays to about 200 rays) is not entirely excluded,[8] the usual quantum theory of radiation and cascade processes seem to be able to explain adequately at least a great majority of the phenomena observed both at sea level and under thirty meters of clay. This conclusion agrees with that deduced from counter experiments[48] or cloud-chamber observations.[50, 51]

6. ACKNOWLEDGMENTS

The data given in this report have been taken from the experiments carried out in the Cavendish Laboratory during 1937–1939. The discussion and some minor calculations of results have been brought up to date, by which we mean up to the end of 1940; no physical periodical since January 1941 is available here.‡‡ Thanks are due the late Professor Lord Rutherford for his permission given to the writer to do research in the Cavendish Laboratory and for his interest in the work, and also to Professor E. V. Appleton and Professor W. L. Bragg. The underground experiments were made possible by the kind invitation of Professor P. M. S. Blackett (now at Manchester) and Dr. H. J. Braddick of Birkbeck College, London, who generously gave valuable help. Last but not least of all, the writer wishes to express his heartiest thanks to Dr. H. Carmichael for putting his apparatus at his disposal, for instructions on the proper manipulation of his electrometer, for constant encouragement, and for valuable discussions and criticisms.

‡ It should be noted here that the same good agreement with Janossy's counter observations is not obtainable by extrapolation of the steep part of Chou's unshielded sea-level curve. With the same counter apparatus, unshielded, at sea level Janossy found only one coincidence per hour. Rough agreement with this value can, however, be obtained by extrapolation of the *lower part* of the sea-level curve. This point will be discussed in the following paper. H.C.

[49] E. P. George, private communication (1939) with the author.

[50] C. Haenny, Comptes Rendus Acad. Sci. (Paris) **206**, 177 (1938).

[51] G. S. Hensby, private communication (1939) to author.

‡‡ In China in 1943. H.C.