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Cosmic-Ray Intensities at Great Depths

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A fourfold Geiger-Müller tube telescope was employed to count the relative number of cosmic rays under different thicknesses of rock. Each Geiger-Müller tube consisted of a 0.125 mm tungsten wire anode and a cylindrical copper cathode 9 cm in diameter and 71 cm in length sealed in a glass envelope filled with hydrogen to a pressure of 9.6 cm of mercury. The experiment was performed in a mine whose shaft was inclined at an angle of 34° from the horizontal. Counts were made at thirty-nine different stations at depths from zero to 1408 meters of water equivalent, where the rate was 5.7×10^{-5} as great as at the surface. When the intensity is plotted against the depth, the resulting curve shows no points of inflection. The effective absorption coefficient decreases from 0.07 per meter of water at the surface to 0.0025 at the greatest depth. If the logarithm of the intensity is plotted against the logarithm of the depth, two straight lines, one from 20 to 250 and the other from 250 to 1418 meters water equivalent from the top of the atmosphere, represent the data well. Shower counts were also made at ten of the stations. These also show a bend at 250 meters. This suggests that there may be two types of very penetrating rays both capable of producing showers. It may be that one of these consists of "heavy electrons" and the other of "neutrinos."

INTRODUCTION

THE famous experiments of Millikan and Cameron[1] on the intensity of cosmic rays in mountain lakes showed a continuous decrease of intensity with depth, which is typical of nearly all cosmic-ray absorption experiments since the early work of Hess and Kolhörster.[2] In 1934, however, J. Clay[2(c)] reported that when he lowered his ionization chamber into the Red Sea, the intensity increased with depth from 200 to 250 meters of sea water, and then decreased rapidly to zero with increasing depth. In the same year, A. Corlin[2] reported a similar increase in the Kiirunavaara mine in northern Sweden. However, this increase appeared between 430 and 520 meters water equivalent. It seems improbable that the number of rays increases, but rather, as suggested by Clay[2(c)] and W. F. G. Swann[3] that the specific ionization may increase by some unknown mechanism. Primarily to test this point, a new experiment has been performed, in which a Geiger-Müller tube telescope was used to count the rays at different depths in a mine.

[1] R. A. Millikan, Nature **116**, 823 (1925); **121**, 19 (1928); Nat. Acad. Sci. Proc. **12**, 48 (1926). R. A. Millikan and G. H. Cameron, Phys. Rev. **28**, 851 (1926); **31**, 163, 921 (1928); **37**, 235 (1931).

[2] For bibliography of these experiments up to 1934, cf. e.g., A. Corlin, "Cosmic Ultraradiation in Northern Sweden," Annals of the Observatory of Lund **4**, (1934). Papers published since that time include: (a) E. Regener, Zeits. f. Physik **100**, 286 (1936). (b) W. Kolhörster, Zeits. f. Physik **88**, 536 (1934). (c) J. Clay, Physica **1**, 363 (1934). (d) J. Clay, Physica **3**, 646 (1936). (e) J. Clay and C. G. t'Hooft, Physica **2**, 1039, 1042 (1935). (f) J. Clay, J. T. Wiersma and G. H. Graaff, Physica **1**, 659 (1934). (g) J. Clay, J. T. Wiersma and C. G. t'Hooft, Physica **1**, 1077 (1934). (h) J. Clay, C. G. t'Hooft, J. L. Dey and J. T. Wiersma, Physica **4**, 121 (1937). (i) D. H. Follett and J. D. Crawshaw, Nature **136**, 1026 (1935); Proc. Roy. Soc. London **A155**, 546 (1936). (j) Auger and Rosenbar, Comptes rendus **201**, 1116 (1935); **202**, 1923 (1936). (k) H. Maass, Ann. d. Physik **27**, 507 (1936). (l) F. Weischedel, Zeits. f. Physik **101**, 732 (1936). (m) J. Barnothy and M. Forró, Zeits. f. Physik **104**, 744 (1937). (n) A. Ehmert, Zeits. f. Physik **106**, 751 (1937). (o) W. H. Pickering, Phys. Rev. **52**, 1131 (1937).

[3] W. F. G. Swann, Phys. Rev. **46**, 432 (1934).

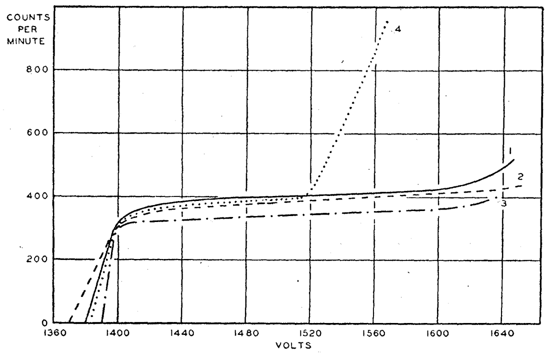

Fig. 1. Geiger-Müller tube counting rates *versus* applied voltage.

The Apparatus

Four Geiger-Müller tubes were arranged for fourfold vertical coincidence. The copper cathodes of these tubes were cylinders 9 cm in diameter and 71 cm long, and the anodes were of 0.125 mm (5 mil) tungsten wire stretched along the axes of the copper cylinders. These electrodes were sealed in glass envelopes, and after thorough cleaning, the tubes were filled with hydrogen to a pressure of 9.6 cm of mercury. The residual counts per minute as taken in the mine are plotted against the voltage in Fig. 1. These curves show the unusually low residual counting rates for such large tubes, the broad operating plateaus, and the degree to which the tubes were matched. Unfortunately, a tube with characteristics similar to number two was broken during the trip from Chicago to Mohawk, Michigan. The tubes were operated at 1480 volts; however, voltage fluctuations in the 110-volt primary, in one instance, caused the secondary voltage to go to 1520 volts, and in another, to drop to 1440 volts. It may be seen from the curves that these voltages are within the working range of all the tubes. The efficiencies at 1480 volts, as determined by the method of Street and Woodward,[4] were No. 1, 97.6 percent; No. 2, 97.8 percent; No. 3, 98.5 percent. These efficiencies were determined in the laboratory where the individual counting rates were approximately 1500 per minute. In the mine where the experiment was performed, the individual counts were consistently 500 per minute or less; thus, the efficiencies were probably higher than indicated above, and were assumed to be constant.

The circuit employed is shown in Fig. 2. One 57 tube was connected directly to the Geiger-Müller tube according to the Neher-Harper circuit.[5] This was done to obtain a quick recovery of the Geiger-Müller tube. The high voltage was supplied by a power pack built according to the Gingrich[6] modification of the Evans[7] type circuit. The grid bias and screen voltage of the Neher-Harper 57 tube and the grid bias of the thyratron were supplied by dry batteries. The other voltages were supplied by a common power pack, equipped with a 350-volt transformer and a type 80 rectifier. The output pulse from the thyratron was put through an impulse counter similar to the type developed by F. Shonka. The assembled apparatus is shown in Fig. 3.

The Experiment

The experiment was performed at Mohawk, Michigan, in the No. 2 shaft of the Seneca Copper Corporation. This mine is especially

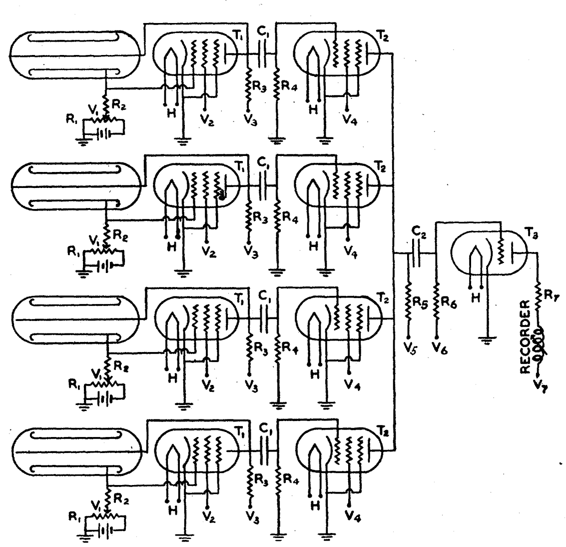

Fig. 2. Diagram of circuit used. T_1 and T_2 are type 57 tubes; T_3 is a type 885 thyratron; $R_1=R_2=R_3=2\times10^6$ ohms; $R_4=5\times10^5$ ohms; $R_5=1\times10^5$ ohms; $R_6=5\times10^4$ ohms; $R_7=6\times10^3$ ohms; $V_1=-4$ volts (about); $V_2=+45$ volts; $V_3=+1480$ volts; $V_4=+90$ volts; $V_5=+250$ volts; $V_6=-47$ volts; $V_7=+300$ volts; $C_1=50$ $\mu\mu$f; $C_2=0.02$ μf; $H=2.5$ volts a.c.

[4] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).

[5] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).

[6] N. S. Gingrich, R. S. I. **7**, 207 (1936).

[7] R. D. Evans, R. S. I. **5**, 371 (1934).

suitable for such an experiment for five reasons: first, the shaft is inclined at an angle of 34° from the horizontal, thus the Geiger-Müller tube telescope could be set up in the shaft under any desired thickness of rock; second, the density of the overlying rock is uniform and well known; third, the surrounding rock is comparatively free from radioactive material; fourth, since the surface of the ground is nearly level, the thickness of the rock could be determined accurately; and fifth, the mine was not in operation, thus permitting ample time for the experiment.

The Geiger-Müller tubes were placed with their axes parallel and 11.5 cm from center to center. In this position, a ray coming down the shaft could not pass through more than one tube, and hence could not be recorded, since the instrument recorded only the simultaneous discharge of all four tubes. Readings were taken with the telescope in the vertical and in the horizontal position, and the horizontal counts, assumed to be due to showers, were subtracted from the vertical counts to give the number of vertical rays. Actually near the surface this correction is too great, since some of the horizontal counts there are caused by penetrating rays traveling nearly horizontally. No attempt was made to correct for the possibiilty of a cosmic ray passing through tubes 1 and 2 simultaneously with another ray passing through tubes 3 and 4, etc. Since this correction will remain very nearly a constant factor, its omission will not change the shape of the absorption curve. The radioactivity of the rock was very low and surprisingly uniform. The accidental counts were one in fourteen days. This was determined by measuring the individual and the twofold counting rates in the mine. The coincidence time of the circuit τ, was calculated from the equation $A_{1,2}=2N_1N_2\tau$, where $A_{1,2}$ is the twofold accidental rate for tubes 1 and 2; and N_1 and N_2 are the individual counting rates. The fourfold accidental counting rate, $A_{1,2,3,4}$, was then found from the equation $A_{1,2,3,4}=4N_1N_2N_3N_4\tau^3$.[8]

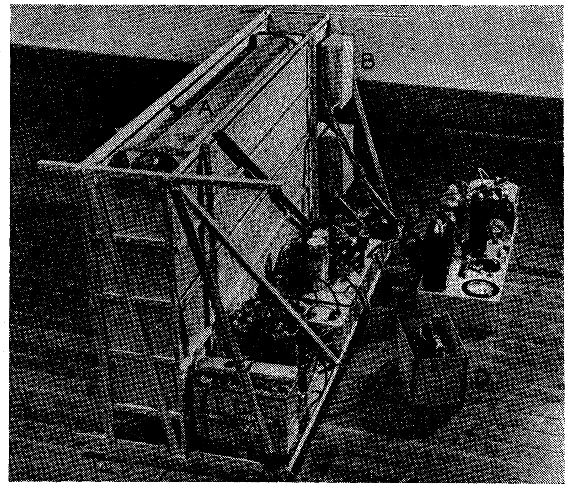

FIG. 3. The apparatus, showing A, the top Geiger-Müller tube; B, the first two stages of amplification; C, the high voltage pack; and D, the recorder.

In order to determine the amount of rock through which the rays must penetrate, the slope of the skipway rails was determined every 100 ft., and the distance of the apparatus from the surface was measured along the rails by a steel tape. A level of the surface ground over the shaft was run, and the vertical distance was corrected for this and for the variation in the ceiling height in the shaft. To express the absorbing material in equivalent depths of water, the rock thickness was multiplied by the density of the rock. The density and thickness of the overlying lava flows, obtained from diamond core drillings, was kindly furnished by T. M. Broderick, geologist for the Calumet and Hecla Consolidated Copper Company. The average density of the rock was 2.875 grams per cc.

DATA AND RESULTS

The main part of the data is given in Table I. The second column, depth in meters water equivalent, was obtained as explained above. The next three columns need no explanation. Column six, counts per minute in the horizontal position, was taken from Table II, to be explained later. In computing the last column, I_0 was taken as 81.4 counts per minute. The probable errors were obtained from the statistical errors in counting ($\epsilon=0.6745N^{\frac{1}{2}}$). Reading number 15 was taken at a depth of 274.6 meters,

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[8] Recent theoretical and experimental studies soon to be published by Carl Eckart and Francis Shonka show that the general equation for the accidental counting rate with n counters, each having its characteristic coincidence time τ, is

$$A_{1,2,\cdots n}=(N_1N_2\cdots N_n)(\tau_1\tau_2\cdots\tau_n)\left(\frac{1}{\tau_1}+\frac{1}{\tau_2}+\frac{1}{\tau_3}\cdots\frac{1}{\tau_n}\right).$$

with the apparatus tipped at an angle of 18° from the horizontal. Similarly, readings 27 and 28 were taken at angles of 60° and 45° from the horizontal at a depth of 652.3 meters, and readings 34 and 35 were taken at 45° and 23° from the horizontal at 1106.7 meters. It was possible for a ray traveling at an angle of 14° 30′ from the center line of the four tubes to pass through all the tubes. When the apparatus was tipped, the difference between the minimum and maximum thickness of rock through which a ray might travel was great. Most of the rays counted probably came through less material than would be indicated by dividing the vertical thickness by the sine of the angle between the horizontal and the line through the center of the tubes. If 7° 15′ was added to this angle, points 15, 27, and 28 would best fit the rest of the data; therefore, 7° 15′ was also added to the corresponding angles to get the effective depths for points 34 and 35. At 398.7 meters, reading 19, it was discovered that the apparatus was slightly out of line in the box. It was assumed that this occurred while tipping the apparatus to 18°. On this assumption, readings 16, 17, and 18 would be slightly low; therefore, on the upward trip reading 36 was taken in this region.

When the apparatus was tipped at 23° from the horizontal at 1106.7 meters (effective depth 2220 meters) only 2 counts were recorded in 2.5 days. This is approximately the shower intensity expected at 1106.7 meters; therefore, it is impossible to say whether these counts were due to showers or to rays coming through 2220

TABLE I. *Cosmic-ray intensities from fourfold vertical coincidence counts.*

Station No.	Depth Meters Water Equiv.	Counts Vertical	Time Min.	Counts per Min. Vertical	Counts per Min. Horizontal	Difference	I/I_0
1	0	11666	140	83.3 ±0.5	2.32	81.0	0.995 ±0.006
2	4.62	3642	67	54.3 ±0.6	1.76	52.54	0.646 ±0.007
3	11.3	3599	101.5	35.4 ±0.4	1.22	34.18	0.420 ±0.005
4	17.0	1791	79	22.7 ±0.36	0.85	21.85	0.269 ±0.005
5	25.4	8818	636	13.85 ±0.10	0.58	13.27	0.163 ±0.0016
6	23.6	15627	1025	15.24 ±0.08	0.63	14.61	0.180 ±0.0010
7	89.1	997	402	2.48 ±0.05	0.17	2.31	0.0284 ±0.0006
8	112.0	1211	720	1.68 ±0.03	0.11	1.57	0.0193 ±0.0004
9	138.7	604	489	1.23 ±0.03	0.08	1.15	0.0141 ±0.0004
10	163.2	673	740	0.909 ±0.02	0.068	0.841	0.0104 ±0.0003
11	186.4	744	1020	0.729 ±0.015	0.055	0.674	0.0083 ±0.0002
12	214.8	628	1128	0.557 ±0.015	0.045	0.512	0.0063 ±0.0002
13	245.4	399	964	0.414 ±0.014	0.032	0.382	0.0047 ±0.0002
14	274.6	267	803	0.332 ±0.014	0.022	0.310	0.00381 ±0.00017
15	645 *	75	1216	0.0617 ±0.005	0.022	0.040	0.00049 ±0.00006
16	304.5	416	1510	0.275 ±0.009	0.017	0.258	0.00317 ±0.00012
17	323.3	268	1246	0.215 ±0.009	0.015	0.200	0.00246 ±0.00011
18	347.0	212	1128	0.188 ±0.009	0.014	0.174	0.00214 ±0.00011
19	398.7	187	1248	0.150 ±0.007	0.012	0.138	0.00170 ±0.00009
20	398.7	179	1196	0.150 ±0.007	0.012	0.138	0.00170 ±0.00009
21	440.8	181	1716	0.106 ±0.005	0.010	0.096	0.00118 ±0.00006
22	497.2	183	2138	0.086 ±0.004	0.009	0.075	0.00092 ±0.00005
23	545.5	216	2955	0.073 ±0.003	0.008	0.065	0.00080 ±0.00004
24	601.8	148	2690	0.055 ±0.003	0.0065	0.0485	0.00060 ±0.00004
25	647.9	116	2474	0.047 ±0.003	0.0054	0.0414	0.00051 ±0.00004
26	652.3	149	3220	0.046 ±0.002	0.0054	0.0409	0.00050 ±0.00003
27	703 *	91	2830	0.0322 ±0.002	0.0054	0.0268	0.00033 ±0.00003
28	820 *	129	4131	0.0312 ±0.002	0.0054	0.0258	0.00032 ±0.00003
29	748.3	105	3304	0.0318 ±0.002	0.0040	0.028	0.00034 ±0.00003
30	840.0	71	2835	0.025 ±0.002	0.0030	0.022	0.00027 ±0.00003
31	940.2	43	2201	0.0195 ±0.002	0.0025	0.017	0.00021 ±0.00003
32	1034.5	34	2791	0.0122 ±0.0014	0.0021	0.0101	0.00013 ±0.00002
33	1106.7	38	3625	0.0105 ±0.0013	0.0006	0.0099	0.00012 ±0.00002
34	1408 *	16	3040	0.00526 ±0.0009	0.0006	0.00466	0.000057 ±0.00001
35	2220 *	2	3532	0.0006 ±0.0003	0.0006	0.0	0
36	336.1	317	1315	0.241 ±0.009	0.0015	0.226	0.00278 ±0.00010
37	72.7	2612	741	3.52 ±0.05	0.18	3.34	0.0410 ±0.0005
38	50.5	3852	612	6.30 ±0.07	0.44	5.96	0.0733 ±0.0008
39	0	115377	1380	83.60 ±0.17	2.17	81.4	1.000 ±0.002

* These points were obtained with the apparatus tipped at various angles.

meters water equivalent. It was assumed that they were showers and that no rays were detected at an effective depth of 2220 meters water equivalent.

As explained above, a ray coming down the shaft could not pass through more than one Geiger-Müller tube; however, to be sure that there was no error introduced by working in the shaft, reading 26 was taken at a position 65 feet into a side drift. There is no detectable difference between the shaft and the drift readings. Points number 34 and number 35 were also taken in a drift.

In Fig. 4, I/I_0 is plotted on a logarithmic scale against the depth below the surface of the ground. For comparison, the points are numbered to correspond to the numbers in column 1 of Table I. The points inside the rectangles represent the readings taken with the apparatus tipped. Apparently, these points are not as accurate as the vertical readings. The fact that there appears to be no systematic difference between these readings and the vertical readings seems to mean that no large part of the rays is diffusely scattered.

The readings with the tubes in horizontal position are given in Table II. These values were plotted against the depth and the figures in column 6 of Table I were taken from this curve.

Discussion

Curve A of Fig. 5 is a plot on a double logarithmic scale of I/I_0 against the depth measured from the top of the atmosphere. These points may be represented either by a curve which is slightly concave downward or by three straight lines. One straight line from 20 to 250 meters

TABLE II. *Counts per minute with the tubes in horizontal position.*

Station Number	Depths in Meters Water Equivalent	Counts per Minute Horizontal
1	0	2.32 ±0.15
5	25.4	0.58 ±0.02
8	112.0	0.109 ±0.002
10	163.2	0.068 ±0.007
12	214.8	0.045 ±0.005
14	274.6	0.019 ±0.003
18	347.0	0.014 ±0.003
22	497.2	0.010 ±0.002
25	647.9	0.0054±0.0009
32	1034.5	0.0021±0.0006
39	0	2.17 ±0.04

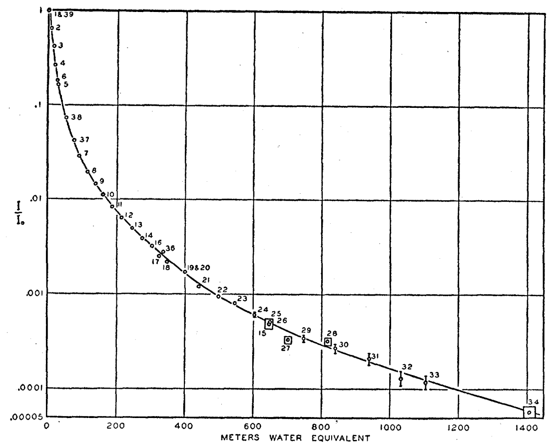

FIG. 4. Cosmic-ray intensity on a logarithmic scale plotted against the depth from the surface of the earth.

and another from 250 to 1420 meters seem to represent the data very well over this wide range. Assuming the validity of such a straight line relation, the analytical expression for the cosmic-ray intensity as a function of the depth is:

$$20 \leq h \leq 250m, \quad I/I_0 = 95.37 \times h^{-1.77},$$
$$250 \leq h \leq 1420m, \quad I/I_0 = 6058 \times h^{-2.52},$$

where h is the thickness in meters water equivalent from the top of the atmosphere.

It is evident from Fig. 4 that the data may also be represented by a group of exponentials. The corresponding absorption coefficients (taken from the slope of the curve) vary from 0.07 per meter of water at the surface to 0.0025 per meter at the greatest depth.

Comparison with Data of Other Observers

While this experiment was in progress, A. Ehmert[2(n)] published a report of a similar experiment performed with threefold Geiger-Müller tube coincidences in water. His values are shown by curve B in Fig. 5. Although his data extend only to one-sixth of the depth of the present measurements, it is interesting to notice how closely the two curves agree to a depth of 240 meters. In making the comparison, the two values obtained at the surface of the earth were equated. Possibly the separation below this point is due to the different transition effects in going from air into water, and from air into rock. The exponent of h for Ehmert's curve is -1.87 as compared with -1.77 above. This may represent

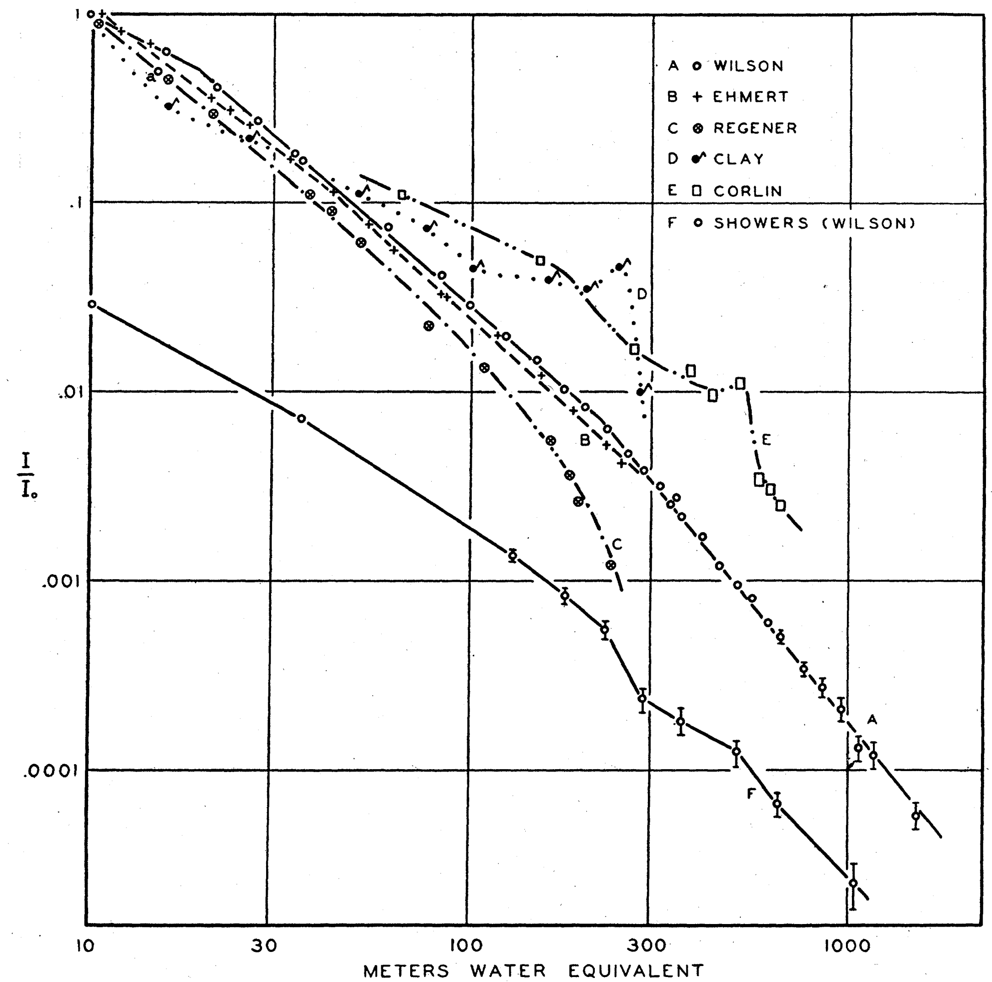

FIG. 5. Cosmic-ray intensity plotted on a logarithmic scale *versus* the depth from the top of the atmosphere plotted on a logarithmic scale.

a real difference, arising because of the different absorbing media or because of the difference in the solid angles subtended by the two telescopes. Ehmert has shown that his values agree closely with those from previous counter tube coincidence experiments. The ionization data of E. Regener,[9] J. Clay,[2(c)] and A. Corlin,[2] equated at the surface of the earth, are shown by curves *C*, *D*, and *E* of Fig. 5. One would not expect the ionization measurements and the coincidence measurements to agree perfectly because an ionization chamber records rays from all directions including showers, whereas a coincidence apparatus records rays from a limited solid angle. The coincidence measurements, however, appear to be more consistent than the ionization measurements, probably because the coincidence apparatus is much less affected by radioactivity in the surrounding medium.

The horizontal counts as given in Table II (assumed to be showers) are plotted in curve *F* of Fig. 5. The apparatus was not designed to record showers, and readings were taken only long enough to obtain sufficient accuracy for correcting the vertical coincidences. Nevertheless, it will be seen that apparent decreases occur in the shower intensity at just the depths at which Clay and Corlin find sharp decreases in ionization. In view of the magnitude of the probable errors of these shower counts, the sig-

[9] E. Regener, Physik. Zeits. **34**, 306 (1933).

nificance of this coincidence is questionable. Curve A, however, also shows a bend at about the same depth. Perhaps this bend at about 250 meters marks the end of one shower producing component.

Ehmert attributes the bend in his curve at 45 meters to a transition effect caused by secondaries which have a range of 35 meters, and are considerably more abundant in water than in air. Similarly, the bend in the absorption curve under rock at 20 meters water equivalent may be attributed to a transition effect. Point "a" of Fig. 5 was taken in air with the apparatus tipped. This indicates that there is no bend in the intensity curve in air alone; thus further substantiating the transition hypothesis. In this case, the secondaries have a range of only about 10 meters of water equivalent. This comparison suggests that the secondaries are much more rapidly absorbed in the rock than in water. Since the curve in rock is slightly above that for water, if the secondaries are more readily absorbed in the rock, they must also be even more rapidly produced in the rock.

Nature of the Rays

W. Heitler[10] has pointed out that if the Bethe-Heitler theory for the absorption of β-rays is valid to infinite energy, then the β-rays (both $+$ and $-$) "with any reasonable energy" must be absorbed in about 10 to 15 meters of water equivalent from the top of the atmosphere. Also it has been shown[11] that for very high energies the absorption of photons is about the same as the absorption of β-rays. Thus one concludes from theoretical considerations that probably the very penetrating rays are not β-rays ($+$ or $-$) or photons. Experiment shows that neutrons are rapidly absorbed by water; therefore, if the penetrating rays are neutrons, one would expect the absorption to be much greater in water than in rock. This is not the case; therefore, the rays are probably not neutrons. According to the theory of Bethe and Heitler, protons should not excite appreciable radiation, and would thus not be expected to produce showers at great depths such as has been observed in this experiment. Heisenberg has suggested that the penetrating rays are "neutrinos" present in the primary rays and also produced as shower secondaries. Also it is very probable that the newly discovered "heavy electrons" could penetrate to the great depth.

Since the penetrating cosmic rays seem to show a new type of absorption, and since they show such great penetration, it seems reasonable to assume that the very penetrating cosmic rays are rays of which at the present time we have little knowledge. One cannot now say whether these rays are "neutrinos," "heavy electrons," protons (if they can produce showers), or some new type of ray. However, since the curves for both the vertical and the horizontal coincidences show a bend at about 250 meters water equivalent, one is led to suggest that there may be two types of very penetrating rays both capable of producing showers. It is not impossible that one of these consists of "heavy electrons" and the other of "neutrinos."

In conclusion, the writer wishes to express his sincere appreciation to Professor Arthur H. Compton for his inspiring direction and generous assistance with this experiment. It is also a pleasure to thank Mr. William F. Hartman, manager, and Mr. J. Ralph Abramson, assistant manager, of the Seneca Copper Corporation for their cooperation in the use of the Gratiot mine and its equipment; Mr. Francis R. Shonka for his assistance in building the Geiger-Müller tubes; and Messrs Haydn Jones, George E. Boyd, John F. Gall, and George G. Wright, Jr. for their help in taking the data.

[10] W. Heitler, Proc. Roy. Soc. London **A161**, 261 (1937).
[11] H. Bethe and W. Heitler, Proc. Roy. Soc. London **A146**, 83 (1934).

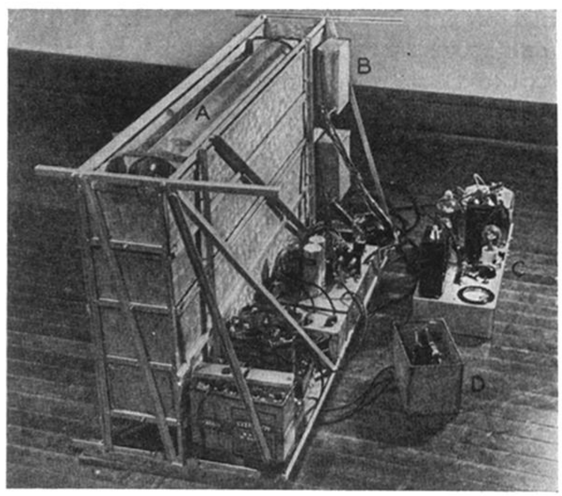

FIG. 3. The apparatus, showing A, the top Geiger-Müller tube; B, the first two stages of amplification; C, the high voltage pack; and D, the recorder.