The Intensity of Cosmic Radiation under Thick Layers

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SINCE 1933 we, at Amsterdam, have been conducting experiments to study the decrease of the penetrating radiation in thick layers of water and earth. This program was partly undertaken on consideration that if there is a complex of radiation, it is possible to gain an analysis by first isolating the most penetrating component.

From an analysis made as early as 1926[1] (Fig. 1) it was obvious, that there were two distinct components, a soft part absorbed in about 10 cm of lead and a hard component, which decreased but very little in 50 cm Pb. It was supposed then, that this soft part was a secondary phenomenon from the hard component. For a few years it was thought, that both were independent; but now we know that at sea level and below the soft rays are the secondaries of the hard component. In a short and preliminary experiment in 1933 we found a strange variation under about 250 m water.[2] This irregularity in the decrease of the radiation in this region was confirmed by two series of experiments in a coal mine.[3,4] However, there could have been a hidden cause of disturbance in the soil, and the density and water equivalence remained uncertain.

It was necessary to confirm or disprove the existence of the irregularity found in water. Therefore, we have tried several different times to measure with sufficient accuracy the intensity in deep water, and succeeded a year ago to find the intensity with an ionization-chamber and counters down to 440 m of water.[5]

The measurements with the counters were performed with two sets of two counters in parallel, with which we found the values without lead, and with 2.5 cm of lead; and one set of threefold in a smaller cone. With another apparatus we found the values in a cone of 30° in every direction and 5 cm Pb between.

In the first 50 m of water the decrease is different for different experimental arrangements. For rays traveling in a vertical direction the decrease is larger than for rays traveling in an oblique direction. Compare the decrease in Fig. 2.

The decrease in the thick layers is most easily represented on logarithmic coordinates, and over a large range of depths the line in such a system is nearly straight. The relation for h in m of water is:

$$I = I_0 h^{-1.93} \text{ between 60 and 400 m water.}$$

This means that the range spectrum of the particles is (see Fig. 3):

$$f(R) = C \cdot R^{-2.93},$$

and if the loss of energy of the particles is nearly all a loss by collision and the specific ionization is nearly constant, the energy distribution is likewise proportional to $E^{-2.93}$.

For the first part of the layers, down to 60 m, the decrease is smaller, which must be ascribed to the disintegration of the mesotrons in the atmosphere. We find from extrapolating the energy distribution found under 50 m of water that the lifetime of the mesotrons is 2.10^{-6} sec. Now from the ionization under 250 m water we find that in this region there must be an excess of secondaries. This is also clear from the in-

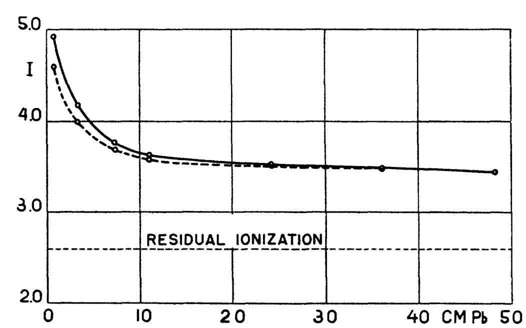

FIG. 1. Clay, 1926. Decrease of ionization in two ionization vessels under 50 cm Pb.

[1] J. Clay, Proc. Roy. Acad. Amsterdam **30**, 1115 (1927).
[2] J. Clay, Physica **1**, 363 (1934).
[3] J. Clay, J. T. Wiersma and G. Graaff, Physica **1**, 659 (1934).
[4] J. Clay, C. G.'t Hooft, C. J. L. Dey and J. T. Wiersma, Physica **4**, 121 (1937).
[5] P. H. Clay, A. V. Gemert and J. Clay, Physica **6**, 184 (1939).

crease of soft radiation (found from coincidences without lead between the counters) in relation to the hard radiation (given by the coincidences with lead between the counters). And in those regions where the excess of ionization is large, we also found a large fluctuation for ionization measurements. These measurements were taken over eight-minute intervals. The sensitivity of the ionization measurements was such that the ionization could be found with an accuracy of 1 percent in the time of eight minutes. At sea level the instruments changed at a rate of 25 scale divisions per sec.

This fact that in the region between 200 and 425 m the amount of secondaries and showers was larger than in the region immediately below sea level was also indicated from the results of Wilson's[6] counter measurements in a copper mine. We see this directly in Fig. 4. But the most evident result was found by Gemert and myself[7]

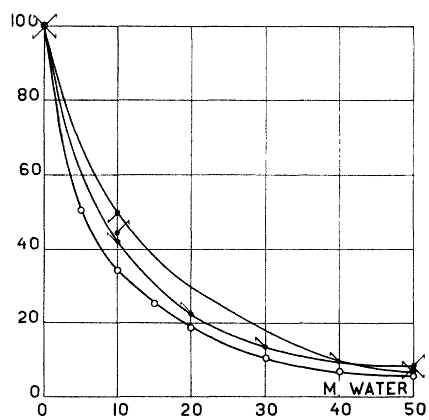

FIG. 2. J. Clay, A. v. Gemert and P. H. Clay, 1939. Decrease of intensity of cosmic radiation in water 0–50 m. o ionization chamber; 2-fold coincidences 0 cm Pb 130°; 2-fold coincidences 2.5 cm Pb 130°; 3-fold coincidences 2.5 cm Pb 90°; 3-fold coincidences 5 cm Pb 30°.

when we made counter measurements in a coal mine with three pieces of counter apparatus; first the instrument which we used in the water measurements, and second with two new pieces of counter apparatus, of 3 sets of 3 counters in parallel, each counter of 47 cm active length and 6 cm diameter. The number of threefold coincidences which we found at sea level when

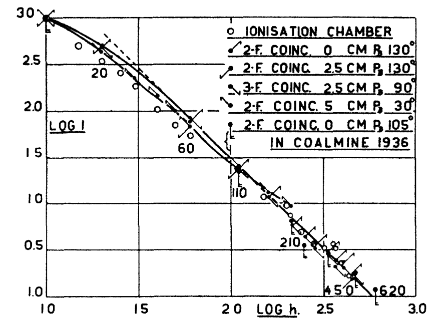

FIG. 3. P. H. Clay, A. v. Gemert and J. Clay, 1939. Decrease of intensity between 0 and 450 m water.

there was 10 cm Pb between the counters was 160 per min., and the resolution time was 2×10^{-6} min.

During the measurements in the coal mine the counters were always protected by 5 cm of lead on all sides, and in this way at 615 m depth (1300 water equivalent), the number of fortuitous coincidences was kept smaller than 0.1 per day.

It was now possible for the first time to find directly the water equivalence of rock by measuring the absorption with the same instruments as we used in water. In Fig. 5, we have compared the values in water and rock. We found, as is seen in Table I, that the water equivalence at 40 and 200 m depth was such that the density of the rock must be divided by 1.19, and then at 219 and 311 there is still an excess of secondaries in rock compared with the values in water. Eight measurements gave us the value of 2.7 for density of the rock. The first 37 m of clay had a density of 2.12. The mean density for the total layer was 2.66. Dr. Nieuwenkamp measured at the same place the mean density between 0 and 615 m by means of

TABLE I. *Water equivalence of rock.*

Depth h	Eq. according to density h_s	According to measurements water-eq. h_e	Density h_s/h_e	Water-Eq. $h_s/1.19$
0	10	10		
43	101	85	1.19	85
102	260	204	1.27	219
143	370	287	1.29	311
195	510	427	1.19	427
255	672			563
375	992			835
495	1320			1107
615	1644			1380

[6] V. C. Wilson, Phys. Rev. **53**, 337 (1938).
[7] J. Clay and A. V. Gemert, Physica **6**, 497 (1939).

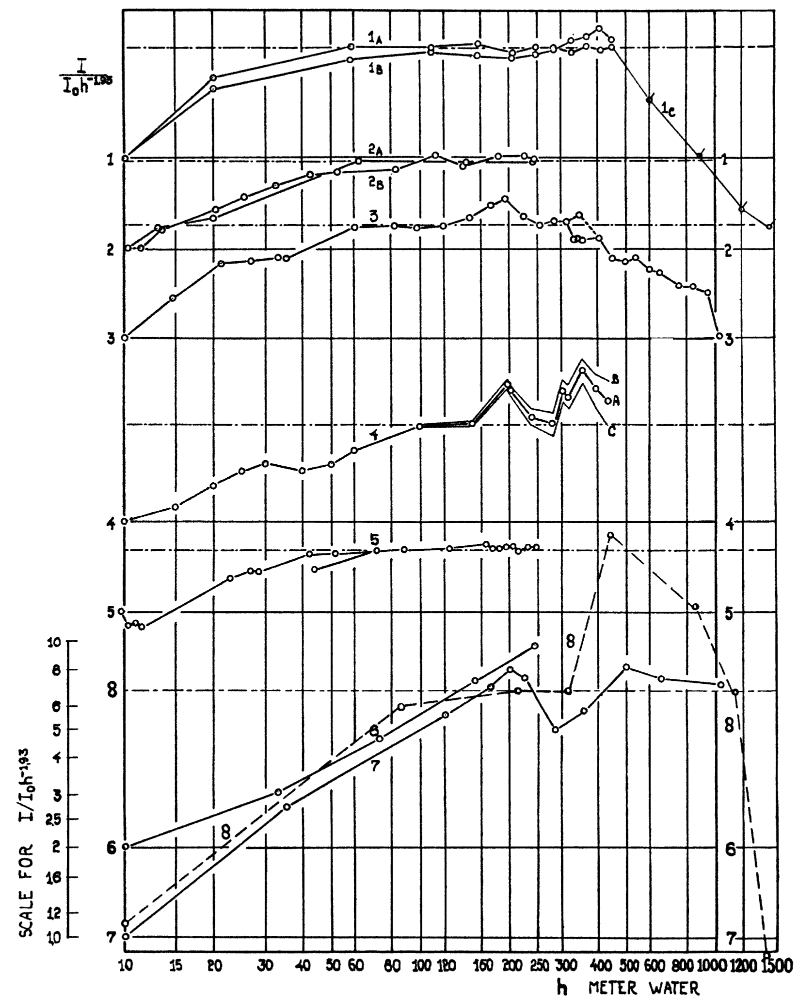

FIG. 4. Decrease of intensity of cosmic radiation by different observers. 1*A* Clay, van Gemert and Clay 10–450 m counters 2*f*, 130°×175°, 2.5 cm Pb. 1*B* Clay, van Gemert and Clay 10–450 m counters 2*f*, 130°×175°, 0 cm Pb. 1*C* Clay and van Gemert 450–1380 m counters 3*f*, 130°×175°, 2.5 cm Pb. 2*A* Ehmert 10–240 m counters 3*f*, 70°×60°, 5 cm Pb. 2*B* Ehmert 10–240 m counters 3*f*, 70°×60°, 0 cm Pb. 3 V. Wilson 10–937 m counters 4*f*, 126°×25°, 0 cm Pb. 4 Clay, van Gemert and Clay 10–450 m, ionization vessel. 5 Weischedel 43–240 m, ionization vessel. 6 Ehmert 10–240 m, showers. 7 V. Wilson 10–937 m, showers. 8 Clay and van Gemert 10–1380 m, showers.

gravity measurements (Hollweck pendulum), finding 2.52±0.10.

From this result we can now conclude that the decrease of the penetrating rays in different materials is not according to density but more in relation to electron density and depends upon the mean binding energy of the electrons.

By measurements with 155 cm Pb between and over the counters, we have found that the absorption in 145 cm Pb is equivalent to 10 m of water. The linear absorption in lead is thus 6.90 times that of water, and in iron 5.6 times that in water. This is very good in accordance with the calculation of Bhabha.[8]

From the measurements with the apparatus in rock and in water we know, therefore, that with

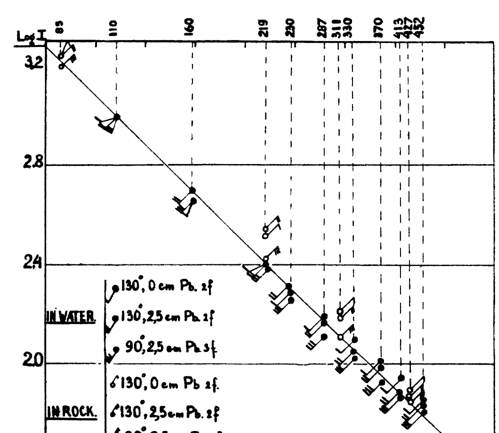

FIG. 5. Clay, A. v. Gemert and P. H. Clay. Comparison of decrease of cosmic rays in water and in rock down to 450 m water equivalent.

[8] H. Bhabha, Proc. Roy. Soc. London **164**, 257 (1938).

TABLE II. *Number of coincidences per day in three instruments at 615 m. The numbers between brackets are the differences from the mean.*

19/10/'38	Time in min.	Number of coincidences G.I	G.II	N_1 (Bergen App.)
20	1332	12 (3)	8 (0)	
21	1427	8 (1)	6 (2)	
22	1396	5 (4)	10 (2)	
23	—	—	—	
24	2848	22 (4)	14 (2)	7
25	1406	10 (1)	10 (2)	4
26	1407	5 (4)	8 (0)	4
27	1464	14 (5)	6 (2)	2
28	1401	14 (5)	8 (0)	3
29	—	—	—	
30	2823	14 (4)	12 (4)	3
1	—	—	—	
2	2656	12 (6)	16 (5)	10
3	1398	6 (3)	11 (3)	4
4	1434	9 (0)	9 (1)	4
5	1472	12 (3)	9 (1)	2
6	—	—	—	
7	3103	21 (3)	21 (5)	7
	25567	164	148	50
Mean Value per min.		0.0064±0.0005	0.0058±0.0005	0.0023±0.0003

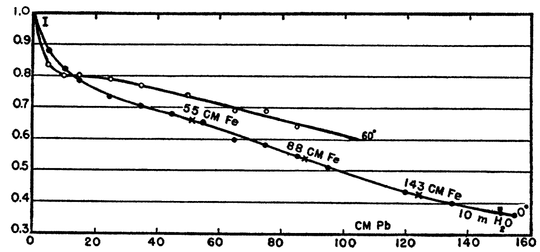

FIG. 6. J. Clay and A. v. Gemert. Comparison of the decrease of 3-fold coincidences for lead, iron and water.

TABLE III. *Number of coincidences at 500 m.*

	Time	Number	Coinc. per min.
*G*1	44842	601	0.0134±0.0005
*G*2	8435	106	0.0126±0.0013

a density of 2.7, which is found nearly the same in other places, the water-equivalent is found to be $2.7/1.19 = 2.27$ and we estimated our water equivalents by multiplying by this value. See Fig. 6. We also used these figures to reduce the results of other experimenters by the same factor in order to compare them with ours.

We experimented in the coal mine at 8 different depths with three instruments of which two were identical. In this way we had a test for the accuracy of the results, and at the same time we could count the coincidences in both instruments when they were placed one next to the other, and find the shower coincidences. In Table II we give the number of coincidences per day, in the three instruments, in the lowest layer at 615 m (1380 m water equivalence). When we take all of these counts, the uncertainty is 6

TABLE IV. *Number of coincidences with 0.5 and 10 cm of Pb between counters.*

Depth	Water Eq.	Log	Time	Number	Number per minute	Reduced	Log
				0 cm Pb			
0	10	1.00	30′	5170	172 ±2.40	22400	4.35
43	85	1.93	58′	445	7.67 ±0.364	1000	3.00
Paraffin			510′	3834	7.52 ±0.122	981	2.99
102	219	2.34	2607′	3150	1.21 ±0.022	158	2.20
143	311	2.49	2758′	1525	0.553 ±0.014	72.1	1.86
195	427	2.63	12658′	3198	0.253 ±0.004	33	1.52
255	563	2.75	10110′	972	0.0961±0.0003	12.5	1.10
375	835	2.92	16520′	515	0.0312±0.0014	4.1	0.61
495	1107	3.04	10032′	150	0.0150±0.0012	1.96	0.29
515	1380	3.14	51134′	310	0.0061±0.0002	0.79	0.90−1
				5 cm Pb			
0	10	1.00	30′	4799	159.9 ±2.31	21800	4.34
43	85	1.93	1184′	8703	7.34 ±0.078	1000	3.00
102	219	2.43	6893′	8042	1.17 ±0.013	159.1	2.20
143	311	2.49	1690′	852	0.504 ±0.014	68.7	1.84
195	427	2.63	1163′	338	0.290 ±0.016	39.5	1.60
				10 cm Pb			
0	10	1.00	24′	3856	160.5 ±2.58	22500	4.35
43	85	1.93	1142′	8132	7.11 ±0.079	1000	3.00
102	219	2.43	6805′	7785	1.14 ±0.013	160	2.20
143	311	2.49	1185′	585	0.493 ±0.020	69.2	1.84
195	427	2.63	7702′	1521	0.197 ±0.005	26.9	1.43
255	563	2.75	2819′	452	0.0802±0.0038	11.24	1.05
495	1107	3.04	53277′	707	0.0132±0.0004	1.85	0.28

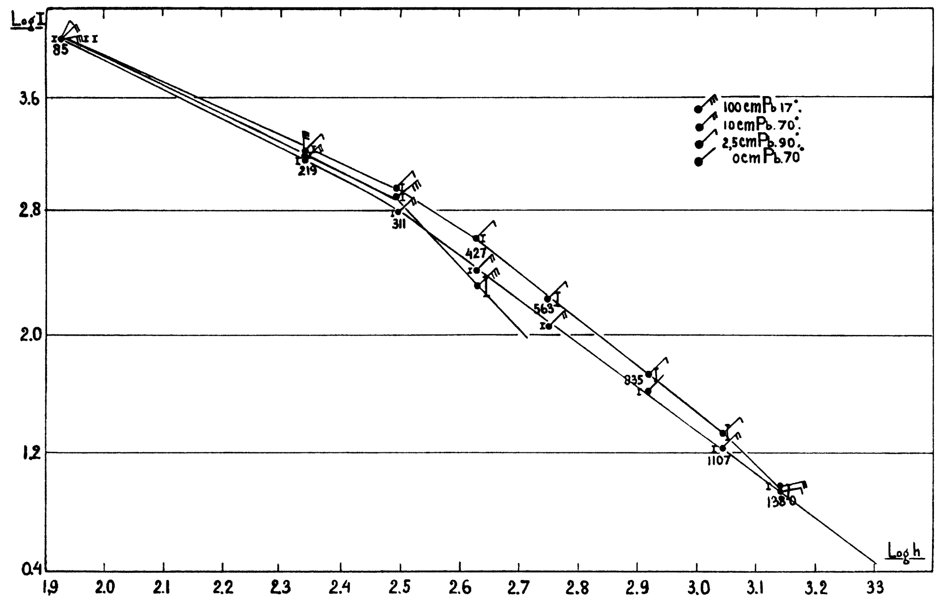

FIG. 7. J. Clay and A. v. Gemert. Decrease of intensity between 85 and 1380 m water equivalent with different systems of counters without lead, with 2.5 cm Pb 140°; 5 cm Pb, 10 cm Pb 70°. Comparison with 10 cm Pb and 100 cm Pb between the counters 17°, between 85 and 427 m water equivalent.

percent. For higher layers the number counted is generally more. At 500 m we found the values given in Table III.

The other values will be found in Table IV, where we also give the number for 5 and for 10 cm Pb between the counters. In Fig. 7 we give the values for different cases and we see that the deviation is not large, but the logarithmic scale, which is necessary in relation to the large range of values, is flattering this to a certain extent.

In Fig. 7 there are also the results for the measurements with the counters separated by 125 cm and with 10 cm and 100 cm Pb between the counters. These measurements were taken in order to test the hypothesis made by some authors as Barnóthy and Forro[9] and Wilson,[6] that the primaries under very thick layers might be neutrinos and that the coincidences would be all secondaries. See Table V. Our results show that at 427 m water equivalent the decrease by 90 cm Pb, which is equivalent as we know now with 6.2 m of water, is 6.3 percent. From the decrease of the intensity at 427 m water equivalent, we should expect a decrease of the primaries of 5.6 percent. The difference between these values is so small that we may conclude that nearly all the primaries at this depth must be ionizing particles. At 219 and 311 where we have said that there are a great many secondaries, the decrease by 90 cm Pb is larger than the decrease we had expected. In this case there are probably secondaries which can penetrate more than 10 cm of lead.

In Table VI we give in column 2 the absorption of primaries in 90 cm Pb (equivalent to 6.2 m of water), calculated from the formula $I = I_0 h^{-1.93}$ At sea level (10 m water equivalent) this formula

TABLE V. *Number of threefold coincidences 17°.*

Depth in m	Time	Number	Number per min.	Reduced	Log I
			10 cm Pb		
10	360′	3929	10.9 ±0.174	15850	4.20
85	1374′	946	0.689 ±0.0224	1000	3.00
219	11484′	1338	0.117 ±0.0032	170	2.23
311	2873′	177	0.0617±0.0046	897	1.95
427	8567′	126	0.0147±0.0013	21.3	1.33
			100 cm Pb		
10	1355′	9626	7.10 ±0.07	10500	4.021
85	534′	325	0.587 ±0.032	870	2.94
219	5229′	543	0.102 ±0.004	162	2.20
311	4055′	230	0.0567±0.003	89.2	1.95
427	8519′	118	0.0138	21.5	1.33

[9] Barnóthy and Forró, Zeits. f. Physik **104**, 744 (1937).

is not of use, the difference is estimated there from the formula given by Bruins.[10] In column 4 the difference is given, and in column 5 the number of particles absorbed in 10 cm Pb is given, and so the total amount of secondaries in percentage is given in the last column.

In Table VII, (Fig. 8) we have given the number of showers found in different layers. The upper portion gives twofold showers. The separate instruments were placed next to another and both were surrounded on all sides by 5 cm Pb. In the lower portion the three sets of counters were placed near each other in this way. The decrease of the showers is given in Fig. 8 where it is also compared with the decrease found by Wilson.[6]

In Fig. 9 we have given the values of the decrease found for the threefold coincidence and we compared them with the values found by Wilson,[6] Kolhörster and Barnóthy and Forro.[9] Under 311 m water equivalent, the decrease of intensity is greater than it is above this layer. It is given by $I=I_0h^{-2.92}$. Has this most penetrating part the same nature and is only the

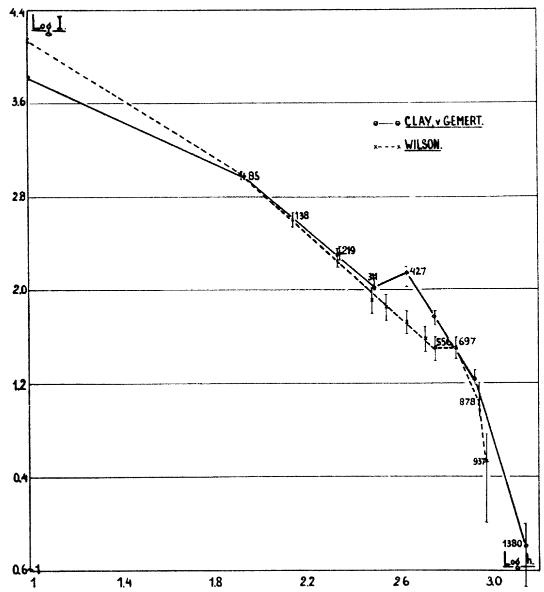

FIG. 8. Comparison of the decrease of showers of different observers.

TABLE VI. *Decrease in 90 cm* Pb *calculated and measured at different layers in percent. Total number of secondaries.*

Water Equivalent	Calculated Decrease of Primaries in 90 cm Pb from Formula 1	Measured in 90 cm Pb	Difference	Secondaries Absorbed in 10 cm Pb	Total of Secondaries
10	27	35	8	12	20
85	14	15	1	7	8
219	5.5	12	6.5	5.8	12.3
311	3.7	8	4.3	11	15.3
427	5.6	6.3	0.7	22	22.7

TABLE VII. *Showers under 5 cm* Pb.

M. Water Eq.	Time	Number	Number per min.	Reduced	Log
			Twofold		
10	1020	1208	1.185 ±0.03	6600	3.82
85	1142	195	0.171 ±0.01	930	2.97
219	1425	54	0.0379 ±0.005	206	2.31
311	4400	92	0.0209 ±0.002	114	2.06
427	2344	60	0.0256 ±0.003	139	2.14
563	5055	53	0.0105 ±0.001	57	1.76
(10 cm Pb (563)	2819	4	0.0015)		
835	7700	24	0.0031 ±0.0006	17	1.23
1107					
1380	25567	3	0.00012 ±0.00007	0.64	0.81—1
			Threefold		
10	547	819	1.425 ±0.0497	7900	3.90
85	1184	218	0.184 ±0.0125	1000	3.00
219	4351	148	0.034 ±0.00279	185	2.27
311	2869	103	0.0362 ±0.00356	200	2.30

TABLE VIII. *Secondaries at different depths.*

M. Water Eq.	130°, Difference between 0 cm Pb and 2.5 cm Pb in percent	70°, Difference between 0 cm Pb and 5 cm Pb in percent	70°, Difference between 0 cm Pb and 10 cm Pb in percent	17°, Difference between 10 cm Pb and 100 cm Pb in percent	Showers Primaries in percent 2 f	Showers Primaries in percent 3 f
10	16	12.4	12.4	10	0.74	0.89
85	10.7	4.3	7.9	2	2.4	2.6
219	13	2.5	5.8	12	3.8	3.0
311	18	10	11	8	4.3	7.3
427	16	18	22	6.4	13	
563			17		13	
835					10	
1107			12			
1379					2	

[10] E. M. Bruins, Proc. Roy. Akad. Amsterdam May. (1939).

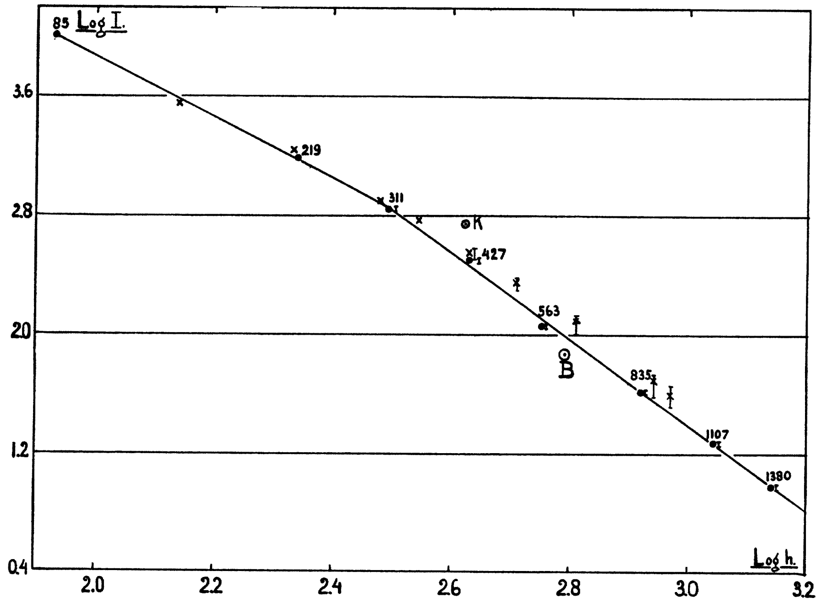

FIG. 9. Comparison of the decrease between 85 and 1380 m water equivalent found by different observers. ● Clay and Gemert; × Wilson; ⊙K Kolhörster; ⊙B Barnóthy and Forró.

energy distribution different? We suppose that in the very deep layers we might have to do with another particle for the following reason. We have measured the amount of secondaries taken away by 2.5 cm Pb, 5 cm Pb, 10 cm Pb, 100 cm Pb and also the number of showers in relation to the number of primaries, and finally the excess of ionization in relation to the intensity of the hardest measured component. From these measurements we found the numbers given in Table VIII and in Figs. 10 and 4. We see that under 200 m water equivalent down to 400 m water equivalent the amount of secondaries, showers and ionization is increasing very fast and at deeper layers the number of secondaries and showers is decreasing again.

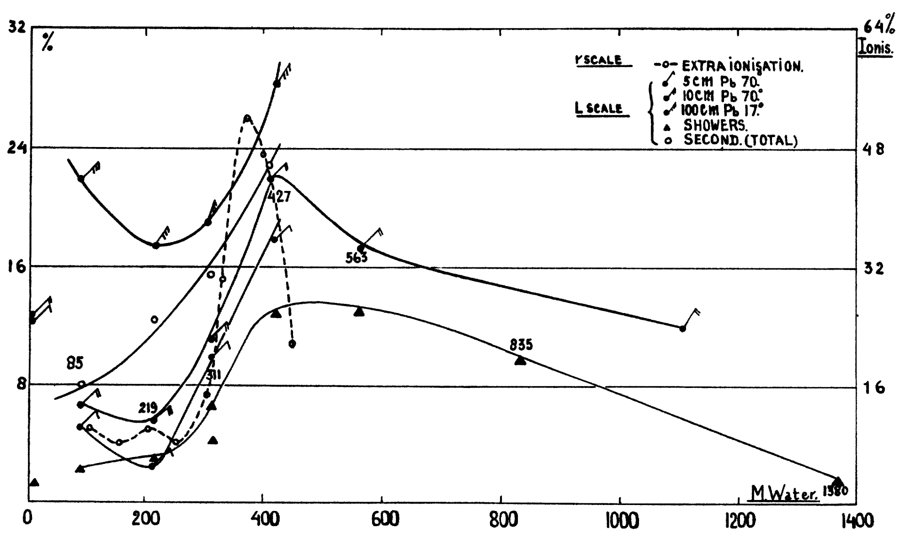

FIG. 10. J. Clay and A. v. Gemert. Secondaries and showers at different depths, left scale. Excess of the ionization, right scale.

As the mean energy of particles below a certain layer is double the value which is necessary to penetrate to that layer, the energy is increasing proportional to the thickness of the layers. We know that 10 m water is equivalent to 145 cm Pb and for lead the absorption for 1 cm Pb is $16 \cdot 10^6$ ev according to Blackett, Wilson[11] and Ehrenfest.[12] The loss in 10 m water must therefore be: 2.4×10^9 volt and in 200 m water will be 4.8×10^{10} ev. At this energy the radiation of the mesotrons begins to be of importance, and for the same reason for thicker layers the specific loss of energy of the mesotrons must considerably increase; so we have no reason to expect it to be reversed for these same particles. When the energy is still higher, the nature of the particles which can penetrate through 400 m water equivalent seems to be different. The production of secondaries and showers is smaller perhaps because the radiation is smaller while the mass is bigger. And these particles are ionizing as we know from the absorption experiment with 1 m Pb at 427 m water equivalent. We suppose, therefore provisionally, that these are protons, but we have learned to be very cautious in the interpretation of cosmic-ray phenomena after so many surprises.

[11] P. M. Blackett and J. G. Wilson, Proc. Roy. Soc. **160**, 304 (1937).
[12] P. Ehrenfest, Comptes rendus, Sept. (1938).