
Physics. — *Decrease of the intensity of cosmic rays in water to a depth of 440 m, measured with counters and ionization chamber.* By J. CLAY, A. V. GEMERT and P. H. CLAY.

(Communicated at the meeting of June 25, 1938.)

Summary.

A description is given of determinations of the intensity of cosmic rays by means of a ionization chamber and two counting-apparatuses in water to a depth of 440 m. The sensitivity of the counters was such that at sea-level in a cone of 130° 120 coincidences per minute were recorded, accuracy 1.2 % per hour. At a depth of 440 m the number was 0.2 per minute. By measuring during 12 hours an accuracy of 8 % could be attained. Some determinations were also made with a conical opening on all sides 30° to a depth of 200 metres.

With the ionization chamber the sensitivity was 25 scale divisions per sec. At a depth of 440 m in 8 minutes determinations could be made with an accuracy of 1 %.

It becomes apparent that at a depth of 200 m and in particular between 280 and 400 m an excess of soft secondary rays is present, so that even over a depth of 80 m no perceptible decrease of ionization is found. This is in agreement with the determinations in the mine at Kerkrade. From this it follows clearly that the decrease in different materials is proportional to the density.

When the results are plotted double logarithmically, the results below 50 m may be represented by

$$I = \frac{I_0}{h^2}.$$

Consequently the distribution of the particles according to the range must be inversely proportional to R^3 and, if the loss of energy in agreement with the results of BLACKETT and WILSON is represented proportional to the energy, the distribution of energy is

$$N(E) = \frac{C}{\left(E + \frac{i}{r}\right)\left\{lg\left(\frac{r}{i}E + 1\right)\right\}^3}$$

This distribution may now at the same time give an explanation of cos^2 distribution of the rays round the vertical.

§ 1. After the determination in the Red Sea and the Gulf of Aden in 1933 in water to a depth of 270 m[1]), the necessity remained to examine further in what manner cosmic radiation penetrates into the material. For this purpose together with WIERSMA and 'T HOOFT [2]) it was tried to make determinations with the Nautilus in the summer of 1934 in the North Sea, in which case we only were able to measure till 50 m with counters and to make determinations till 200 m with the ionization chamber.

In the summer of 1935 we were invited by Prof. TRUMPY of Bergen, with the aid of the exploration ship, the Armauer Hansen, to make determinations in the Norwegian Fjords in the neighbourhood of Bergen and in collaboration with Mr. 'T HOOFT and myself [3]) after great trouble only two accurate determinations at 100 and 200 m could be made with the ionization chamber. After that two apparatuses in succession were destroyed by the water pressure.

A series of counter determinations were made down to 300 m in collaboration with P. H. CLAY [4]). The latter determination enabled us to demonstrate that the intensity of the ionization chamber, containing the total intensity of all rays with their secondaries, runs nearly parallel to the intensity of the primary corpuscular radiation and at the same time that this hard primary radiation produces a shower radiation which runs parallel to the primary radiation.

Afterwards determinations were made in collaboration with DEY, 'T HOOFT and WIERSMA [5]) in the mine at Kerkrade, which confirmed what had been stated after a previous determination, viz. that the intensity did not decrease uniformly with the depth.

A difficulty was offered by the fact that in the mine at Kerkrade layers of slate and sandstone alternate and that it is not an easy matter to determine the density of the layer accurately. In order to avoid these uncertainties it was advisable to examine once more the intensity of

---

[1]) J. CLAY. Phys. 1, 363 (1934).

[2]) J. CLAY, J. T. WIERSMA, C. G. 'T HOOFT. Phys. 1, 1077 (1934).

[3]) J. CLAY, C. G. 'T HOOFT. Phys. 2, 1039 (1935).

[4]) J. CLAY, P. H. CLAY. Phys. 2, 1042 (1935).

[5]) J. CLAY, C. G. 'T HOOFT, L. J. L. DEY, J. T. WIERSMA. Phys. 4, 121 (1937).

radiation below thick layers of water. The determination of REGENER [6]) and his collaborators went as far as a depth of 230 m in the Lake of Constance but a deeper spot was not to be found there.

According to REGENER's method a large vessel, in which the recording measuring instruments are enclosed, is anchored at the bottom of the lake and remains there for a long time, e.g. a week or a fortnight, before it is drawn up again. This method would offer very great difficulties in deeper water.

That is why already some years ago we had applied another method. The measuring instruments were enclosed in a steel tube and this was hung from a steel cable which could be lowered from the ship and drawn up again. Through the cover of the tube a rubber cable with 10 wires was introduced, connecting the instruments inside the vessel in the water with the measuring apparatus on the boat. The determinations which were made for the first time in this way in the Red Sea and the Gulf of Aden yielded some remarkable facts concerning the course of the intensity [1]), on which it was important to obtain certainty.

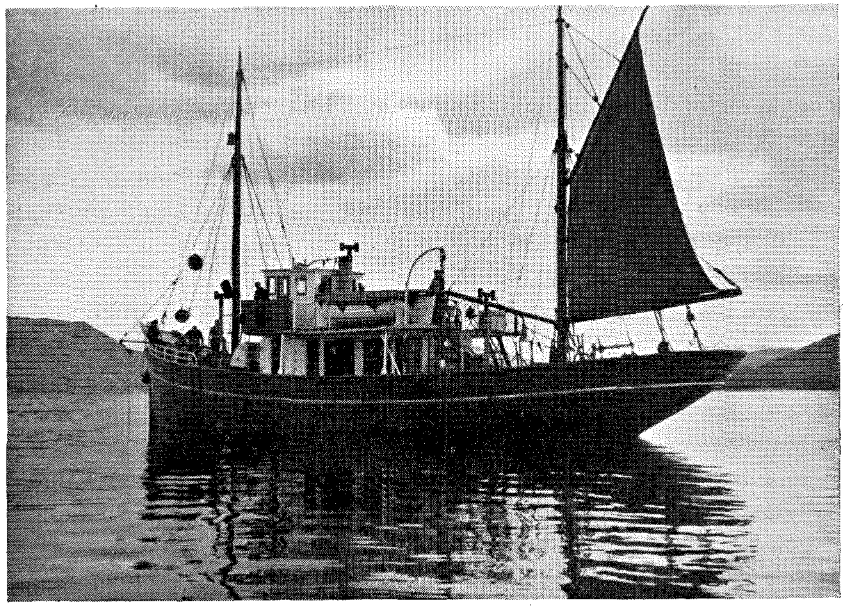

Fig. 1. The „Johan Hjort" in the Sörfjord.

§ 2. For our latest experiments in May the counter determinations were attended to by Mr. VAN GEMERT. The counter determinations were meanwhile so far improved that we were able even at a great depth to measure the small intensity with sufficient accuracy in a short time. Three sets of three counters of 27 cm active length and 4 cm diameter were connected parallel to each other and thus we obtained on the surface of the sea a number of coincidences of 120 and 137 impacts per minute. This number was reduced to about 0.2 per min. at a depth of 440 m, but also in this case consequently in a measuring period of about 12 hours an accuracy of 8 % could stil be obtained. At the greatest depth which we could reach we were able to measure 166 impacts. The number of corpuscles observed at that depth amounted to 0.16 % of the number at sea-level. At sea-level an accuracy of 1.2 %, could be attained in 1 hour. Since we know from various determinations that the radiation is not at all isotropic and not equally penetrative in all directions either, it was advisable to make the counter determinations under different conditions. For this purpose three rows of three counters were placed above one another and the following determinations could be carried out.

---

[6]) E. REGENER. Zeits. f. Physik **74**, 433 (1932).
W. KRAMER. Zeits. f. Physik **85**, 411 (1933); **100**, 286 (1936).
F. WEISCHEDEL. Z. f. Physik **101**, 732 (1936).
A. EHMERT. Z. f. Physik **106**, 751 (1937).

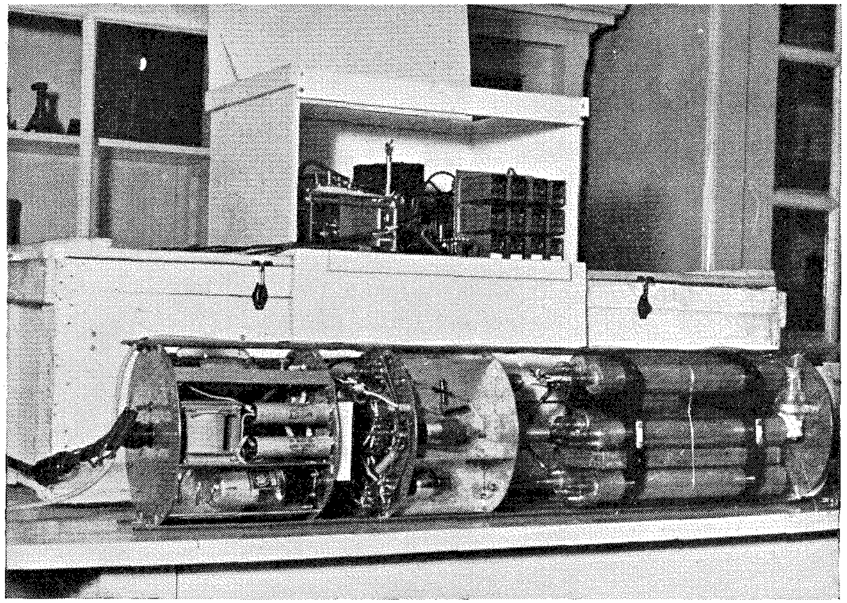

Fig. 2. The counterapparatus.

1. simple impacts.
2. coincidences within 130°, 0 cm of *Pb*.
3. coincidences within 130°, 2.5 cm of *Pb*.
4. triple coincidences within 90°, 2.5 cm of *Pb*.
5. double coincidences within 30°, 5 cm of *Pb*.

The latter determination could be performed with a second apparatus, the angle in *both directions* being equally large, viz. 30°. With the latter counters, consequently, only the vertical bundle was measured and in this case only the vertical rays were measured which could penetrate 5 cm of *Pb*. In this way various properties of the rays could be judged, namely the lateral boundary of the bundle and the hardness.

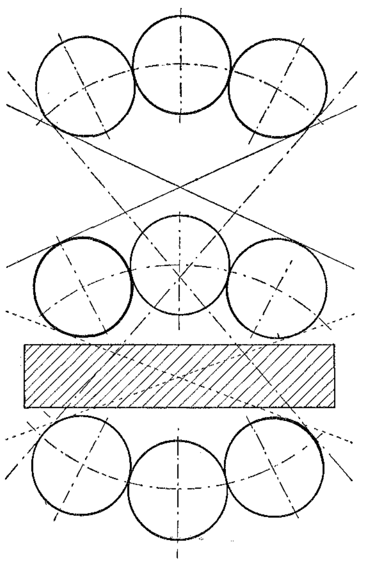

Fig. 3. Arrangement of the counters. Inner diameter of the counters 4 cm.

Together with the instrument to obtain the high tension and the various emplifying circuits the counter apparatus was placed in a steel tube with a length of 100 cm, a diameter of 24 cm and a thickness of the wall of 7.8 mm, closed by a flange, through which the electric cable was introduced. An alternating current of 220 Volt was passed through the cable and only the various current impacts and coincidence impacts were transmitted upwards, counted and registered. At the determination of the large numbers of impacts the corrections were made which had been determined by a separate investigation in order to eliminate the dead time of the counting apparatuses. They were only needed for the values at sea-level and at a depth of 10 m. All this will be described more in detail.

§ 3. The determinations with the ionization chamber were attended to by Mr. P. H. CLAY. The sensitivity was considerably increased as compared to that before and all arrangements had been corrected. The ionization chamber had a capacity of 28 L. filled with argon 60 Atm. On the wall a tension had been produced of 140 Weston elements. The current was measured by an electrometer tetrode in bridge connection according to BARTH [7]). The heating current was stabilized. Behind this bridge a compensating balance had been placed, which increased the number of scale divisions per m. Volt 20 times. A considerable change in the tension of the batteries had no perceptible effect on zero point. Particular attention was paid to the making and breaking of the contacts so that no leaps could occur. The sensitivity of the measuring apparatus with the aid of a weston micro-amperemeter was ultimately such that 1 scale division corresponded to 0.2 millivolt on the grating of the tetrode. Consequently the cosmic radiation at sea-level caused *a shifting of 25 scale divisions per sec,* so that even at the lowest intensities yet a shifting of 15 scale divisions per minute could be observed. During eight minutes of observation, therefore, a shifting of 150 scale divisions was obtained,

---

[7]) G. BARTH. Z. f. Physik **87**, 399 (1934).

while this sensitivity could made completely efficient. However, the measuring was carried out in such a way that the added charge was constantly compensated. The results wil be first discussed in general.

§ 4. With the ionization chamber we have to deal with the rest ionization, which results from the ionization in the apparatus and the ionization due to the radioactivity of the sea-water. This radioactivity may be checked by means of individual counter determinations.

In the mine at Kerkrade at a depth of 260 m below a screen of 12 cm of iron and 15 cm of lead is the same vessel a ionization remained of 0.9 % of the ionization by cosmic rays at sea-level.

Evidently the water of the Fjords is more radio-active than the iron and lead which we used as a screen in the mine, for at a depth of 440 m 2 % of the intensity at sea-level remained. In counter determination 2 as well as 3 at a depth of 440 m still 0.16 % of the value at sea-level remains. If we accept this ratio also for the determinations with the ionization chamber, we find that for 240 and for 100 m the result of the ionization chamber is in perfect agreement with that of the counters. It appears then that the radioactive radiation of the sea-water plus the rest radiation of the apparatus in this case must be 1.6 % of the radiation at sea-level, i.e. 0.7 % more than remained in the mine. Consequently the radioactivity of the sea-water must be at least equal to this value.

This radioactivity was measured directly by us by means of the emanation developed by the water. The emanation which had been found corresponded to a radiation which in our case in the vessel causes about 0.5 % of the ionization of cosmic rays at sea-level. These determinations will be described in a separate paper.

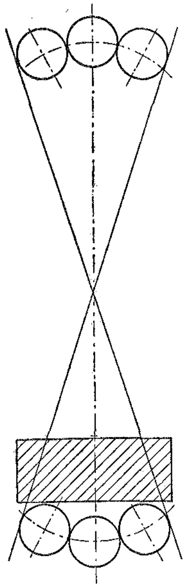

Fig. 4. Arrangement of the second counter apparatus. (Small angle).

§ 5. Evidently in broad outlines there is a parallelism between the hard corpuscular rays and the total ionization measured with the ionization chamber (fig. 5). Yet, in certain areas there are differences between the hard rays (arrangement 3 and 4), the secondary rays (arrangement 2) and the ionization determinations exceeding by far the accuracy of the determination. Immediately below sea-level a distinct deficiency of ionization sets in, which probably may be explained by a relative shortage of the photons (fig. 6). An excess is found at a depth of about 200 m, but particularly a strong secondary radiation is observed between 280 and 400 m. In this area the nature of the radiation is highly susceptible to fluctuations, whereas this is not the case at 440 m. This secondary

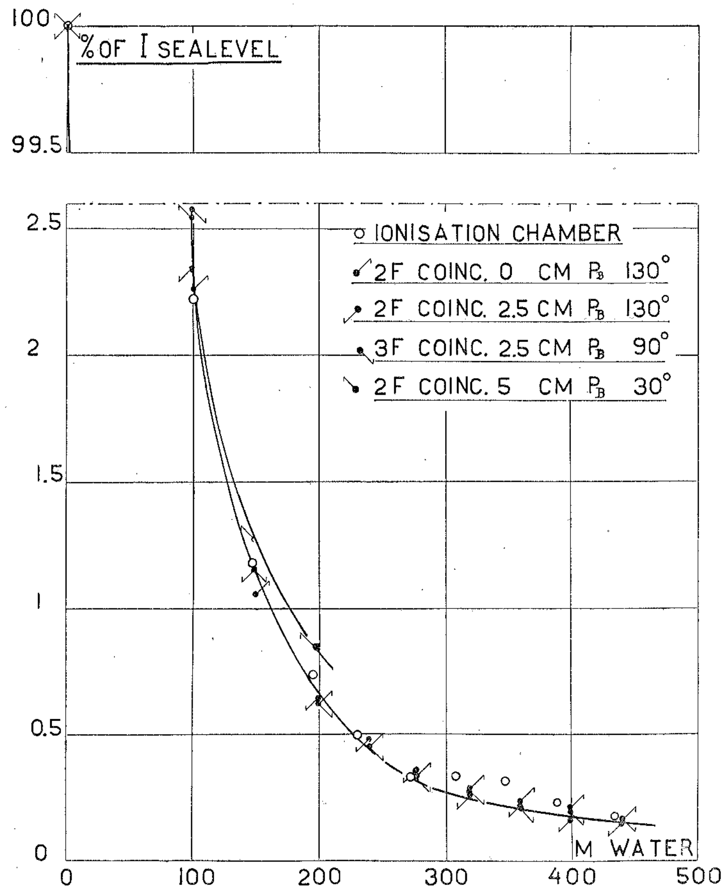

Fig. 5. Decrease of the intensity (measured with counters and ionisation-chamber) in water between 0 and 440 m.

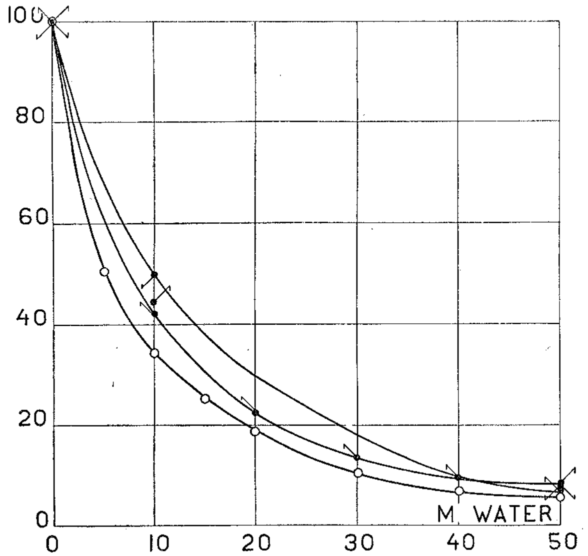

Fig. 6. Decrease of intensity between 0 and 50 m of water.

radiation is so strong that the total radiation in this area does not diminish and even at a deeper point may temporarily increase, as we observed before. To a certain extent the same applies to counters and what we find there will depend on the limit of hardness which is allowed, while

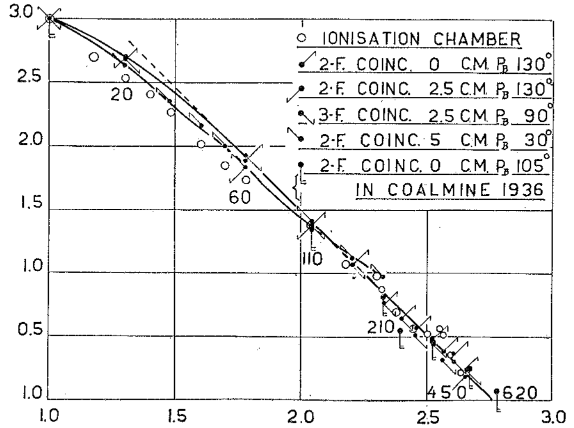

Fig. 7. Decrease of intensity on double logarithmic scale between 0 and 620 m water aequivalent below the top of the atmosphere.

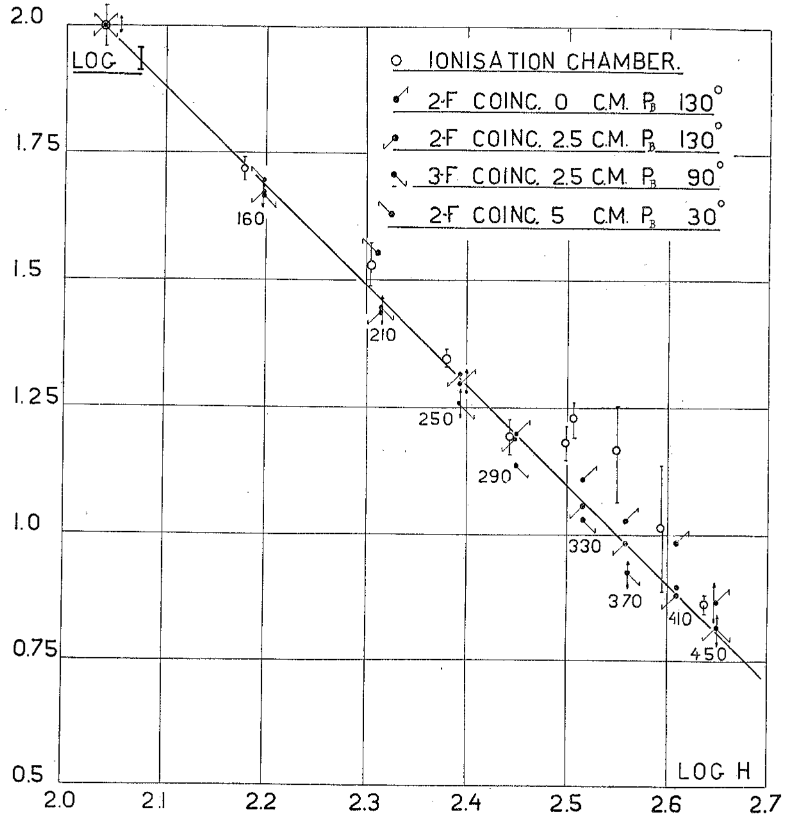

Fig. 8. Decrease of intensity on double logarithmic scale between 110 and 450 m water under top of the atmosphere.

the angle of the opening will play a part as well. Thus it may be explained that these peculiarities in the radiation have not yet been observed by others, while we found the previous irregularity since we paid mainly attention to the soft radiation *).

If we plot the results in a double logarithmic diagram, as was done for the first time by EHMERT 6), the measuring points of the hard radiation practically lie on a straight line. The gradient of this line indicates how the intensity changes with the depth. It is obvious that in this way the area of great depth is highly compressed and not accurately represented. It appears besides that the part from 0 to 10 m does not lie on the line at all and that the part from 10 to 50 likewise slightly deviates.

Irrespective of all these peculiarities, we find that

$$I = \frac{I_0}{h^n}.$$

From our data we found $n = 1.96$, so we may approximately put $n = 2$. EHMERT 6) found $n = 1.87$, while WILSON 7a) who measured in a copper mine to a depth of 1100 m water equivalent for the layers above 250 m water equivalent found $n = 1.78$ and for the values below this $n = 2.50$. This sudden drop in the line is not found by us. However, the difference in the geometry of the counters may play a part here. From fig. 7 we can see that we may indeed assume that the rays decrease in proportion to the density of the material, for the observations in the mine, which on the ground of this relation are converted to water equivalent thickness, lie on the line for the observations in water. If now the decrease is inversely proportional to h^2, this means at the same time that the number of rays in a direction at an angle α to the vertical must be proportional to $\cos^2\alpha$, as this is indeed found by numerous investigators, first by MEDICUS 8), by FOLLET and CRAWSHAW 9) below 25 m of clay, and also by ourselves 10). But from this we may deduce that the distribution of the particles, according to the length of their paths, is inversely proportional to R^3, R representing the path length.

§ 6. If now for these particles it is assumed that the decrease of energy is proportional to their energy, as had been found experimentally by BLACKETT and WILSON 11) between 2 and 6 milliards of Volts, and besides that probably yet a constant amount must be added for the ionization i, as was suggested by various investigators, e.g. SWANN 12), GROSS 13), PFOTZER 14), and others, so that $dE/dx = -i - rE$, the range may be derived from

$$R = \frac{1}{r} lg\left(\frac{r}{i}E + 1\right)$$

and the distribution of the energy of radiation may be found. We see then that the distribution of the energy of the particles is given by

$$N(E) = \frac{C}{\left(E + \frac{i}{r}\right)\left\{lg\left(\frac{r}{i}E + 1\right)\right\}^3}.$$

Plotting this function, we find a distribution between 5.10^9 and 10^{11} e-Volt, as has been reproduced in the figure 9.

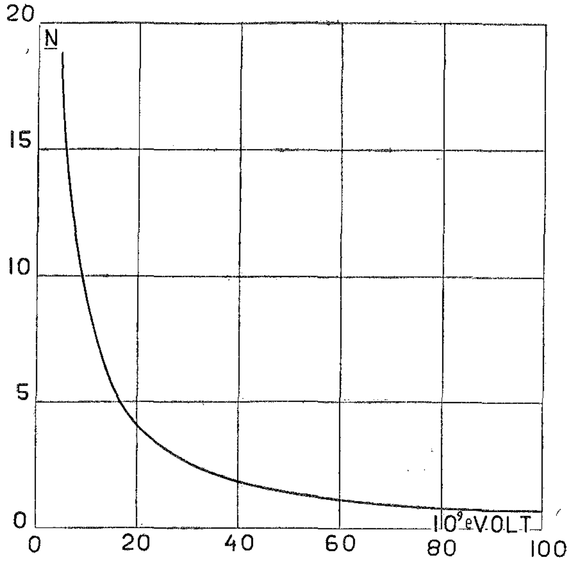

Fig. 9. Energy distribution curve of the hard component of the cosmic rays.

This distribution may be better in agreement with the statistics found by BLACKETT 15) for the energies in the WILSON chamber. But this curve upon the whole corresponds to all experimental data which we know concerning the decrease in water to deep layers, also to the $\cos^2$ distribution found round the vertical, and at the same time explains why this distribution must be found for all depths. Obviously this law of distribution does not apply to low energies. Moreover, at sea-level it would be entirely disturbed for the low energies by the absorption in the atmosphere.

---

*) A. EHMERT 6) thought that our results obtained in the mine below 230 m to 350 m water equivalent were wrong, in spite of the fact that his determinations went no deeper than 230 m, and he has theorized about the question why these mistakes could be made. Evidently there was no reason to do so.

7a) V. WILSON. Phys. Rev. **53**, 337 (1938).

8) G. MEDICUS. Z. f. Physik. **74**, 350 (1932).

9) D. H. FOLLET, J. D. CRAWSHAW, Proc. Roy. Soc. **155**, 546 (1936).

10) J. CLAY, J. T. WIERSMA en K. H. J. JONKER. Proc. Kon. Ned. Ak. Amsterdam **41**, 706 (1938).

11) P. M. S. BLACKETT and J. G. WILSON. Proc. Roy. Soc. **160**, 304 (1937).

12) F. G. SWANN. Phys. Rev. **46**, 828 (1934).

13) B. GROSZ. Phys. Zeits. **37**, 12 (1936).

14) G. PFOTZER. Z. f. Phys. **102**, 23 and 41 (1936).

15) P. M. S. BLACKETT. Proc. Roy. Soc. A **159**, 1 (1937); A **159**, 19 (1937).

Further it starts from the supposition that there is a continuous distribution. However, there may be in some places small irregularities, causing the excesses of secondary rays at a depth of 200 m and particularly between 280 and 360 m.

§ 7. It is worth while now in connection with the determinations to discuss briefly the nature of the hard penetrating radiation, since during the latter months a new conception has been formed. The cosmic radiation consists of two components, which may be ascertained most easily if we measure the decrease of the rays through lead. On enlargement of the layer of lead that has to be penetrated from 0 to 10 cm the radiation decreases quickly to 70 % and what remains is the hard radiation which decreases only 0.5 % per cm of lead.

Until recently this was taken for a protonic radiation. When the energy of a proton is great, the path in the WILSON chamber cannot be distinguished from that of an electron. This is due to the fact that the ionization of the charged particle is dependent on the charge and the mass. This charge of proton and electron is the same and above an energy of a milliard of Volts the mass of the electron is also practically equal to that of a proton.

The behaviour of the less penetrating component is now well known by the researches on absorption in the WILSON chamber by ANDERSON and NEDDERMEYER 16), BLACKETT 11) and his collaborators and LEPRINCE RINGUET 17) and is in agreement with the theory of BETHE and HEITLER 18), CARLSON and OPPENHEIMER 19) while we known now from the latitude-effects in the higher layers of BOWEN, MILLIKAN and NEHER 20) that these relations also apply to the high energies which are necessary for the penetration at the magnetic equator, i.e. for energies above 1.5×10^{10} e-Volt.

But this shows clearly that these electrons can hardly penetrate to sea-level.

The rays which at sea-level can penetrate more than 30 cm of *Pb* consequently cannot possibly be electrons. These form 70 % of the total number. For several years it was thought that they were protons, but recently it has been doubted whether this is the case. When a proton is at the end of its path, i.e. when its energy is less than 10^8 e-Volt, it may be easily distinguished in the Wilson chamber from an electron. The number of ions per cm of the path is then considerably larger than with electrons of the same energy. A combination of curve measuring of the path in the magnetic field with the determination of the specific ionization consequently clearly shows whether we have to deal with protons of a lower energy.

---

16) J. ANDERSON and S. NEDDERMEYER. Phys. Rev. **50**, 263 (1936).

17) L. LEPRINCE RINGUET and CRUSSARD. C. R. acad. Sc. **204**, 240 (1937).

18) H. BETHE and W. HEITLER. Proc. Roy. Soc. A **146**, 83 (1934).

19) CARLSON and OPPENHEIMER. Phys. Rev. **51**, 220 (1937).

20) S. BOWEN, R. MILLIKAN and H. V. NEHER. Phys. Rev. **52**, 80 (1937).

Such terminating paths of the protons now have been found in a far smaller number than was to be expected and therefore at the present moment the conviction begins to gain ground that the penetrating rays cannot be protons 21). Several investigators observed some paths, where from the combination of path curve and specific ionization could be deduced that these are particles of a mass of about 200 times that of the electron. The attractiveness of this supposition is yet considerably increased since it becomes apparent from another side that this very particle may perhaps supply the key for the understanding of two other phenomena, in the first place of the attraction between the proton and the neutron 22). This attraction is of the same kind as that of the homopolar binding in the molecule, i.e. an exchange force. In the case of the binding proton-neutron the particle must have a charge and according to the hypothesis of Yukawa the mass must be about 200 m_0 (m_0 rest mass electron). However, since this mass is equivalent to 10^8 e-Volt and most nuclei cannot produce such an energy, this particle is not liberated in nuclear processes. In the second place it is possible by means of this particle to understand the beta spectrum of the radioactive nuclei.

At the collision of the very energetic electrons of cosmic radiation it is possible that these particles are liberated.

The questions which now arise are in the first place whether these heavy electrons are produced by the ordinary electrons and, if so, in which processes this takes place and in what manner these particles finally disappear into the material. It is most probable that, when the energy begins to grow small, i.e. below 10^8 e-Volt, they stand a great chance on colliding with an atomic nucleus to be absorbed by it and to transmit energy to the nucleus as a whole. If this is the case, it will in all probability lead to a secondary radioactivity of the nucleus, i.e. in a layer of lead of 1 cm 1 process per 100 cm^2 will occur per minute.

In any case the various phenomena occurring at the penetration into the matter must show us the nature of this particle and a thick homogeneous layer as in the case of water is particularly suited to this purpose.

We wish to express our thanks for the great help received during the preparation of this research, in the first place to Prof. B. TRUMPY of Bergen, to the Managing Board of the Johan Hjort for the use of the ship and to the captain and the crew of the „Johan Hjort" for their great willingness and care during the experiments, to Mr. N. BREEDEVELD for his valuable assistance in the construction of the instruments and help during the experiments, to the Hollandsche Draad en Kabelfabriek for the excellent cables made for our investigation.

---

21) H. J. BHABHA. Proc. Roy. Soc. A **164**, 257 (1938; Nature **141**, 117 (1938).

22) H. YUKAWA. Proc. Uh Math. Soc. Japan **17**, 48 (1935).