coming particles[8] (0.3 percent); (2) decrease of the probability of disintegration of the mesotrons by increase of their energy (0.1 percent); (3) change in the radius of curvature of the rays through increase of their energy, which effect is equal to that produced by a decrease of the intensity of the earth's magnetic field.[6, 7] This portion of the change can be calculated from the value of the magnetic effect and is always proportional to it. To calculate from these three components the amplitude to be expected for the sidereal wave, we have still to multiply their sum by a factor F, which depends on the maximum and minimum value of the angle between the direction of the translatory motion and the direction of the incoming rays. In our latitudes (47° 30′) and for apparatus with wide aperture F has the mean value 0.2. Hence we obtain finally as the amplitude to be expected with a vertical arrangement of wide aperture 0.3 percent and with a shower arrangement 0.06 percent, since for showers only part (1) is efficacious as (3) is ineffective because of the missing magnetic effect and (2) is compensated through the simultaneous diminution in the shower production. We can see that these values agree fairly well with the experimental results.

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[8] A. H. Compton and I. A. Getting, Phys. Rev. **47**, 817 (1935).

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Cosmic-Ray Particles at Great Depth

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DURING the year 1938 we have performed measurements of cosmic radiation in a coal mine at 980 meters water-equivalent depth.

We have determined the twofold and threefold counting rates for the same distance between the top and bottom G-M tube when the entire absorber between the tubes consisted only of the tube walls and was equivalent to 0.4 cm Pb. Because of the good resolving time of the circuit employed ($\vartheta = 1.4 \times 10^{-6}$ sec.) the accidental counts were, even for the twofold coincidences, less than $\frac{1}{10}$th of the recorded counts. The efficiency of the G-M tube was found to be 5 percent, whereas at sea level it was nearly 100 percent. This can be explained by assuming that the major part of the radiation, measured with twofold coincidences and with only thin layers of material between the tubes, consists of feebly ionizing rays.

The solid curve of Fig. 1 represents the data and their probable error obtained with twofold coincidences when the thickness of the absorbing layer between the tubes was varied from 0.2 cm Pb up to 1.4 cm Pb. The arrangement was shielded from both sides with 15 cm Pb. The number of the accidental counts and those produced through showers (6/hour) were subtracted from the values obtained. The whole curve was measured three times and the positions of the maximum and minimum were always found at the same thickness of lead. The same experiment was then repeated with the whole arrangement turned through 90°. In this case only horizontal rays or rays deviating therefrom not more than 40° could produce coincidences. The dotted line represents the results obtained. We observe: (1) that the value of the intensity and its decrease with interposed lead is equal to that of the vertically incident rays; and (2) that there is apparently no trace of a maximum.

These results, together with those found in connection with the efficiency of the counters, lead to the conclusion that the absorption corresponding to the dotted line is due in both cases to photons, which have, as it is well known, an efficiency of 2 or 3 percent, and it seems not unlikely that they are of radioactive origin. On the other hand, the maximum must be regarded as a characteristic feature of the vertical radiation and perhaps is caused by γ-rays produced by cosmic radiation. If there is no lead between the counters, the efficiency of these rays in producing twofold coincidences will be very small, but in a sufficiently thick layer of lead they are able to create cascade electrons. Thus the counting rate increases considerably, since now the feebly ionizing γ-radiation is obliged only to discharge the upper counter. The lower counter is discharged by the electrons. This may explain the maximum found for 0.7 cm Pb. The whole phenomenon can be described by a Rossi curve but the maximum of the intensity is found at half as great thickness of lead as at sea level. This result is consistent with our previous conclusions drawn from our experiments performed two years ago,[1] namely that at great depth the majority of the ionizing radiation consists of shower particles, which are softer than the particles of the showers at sea level.[2]

Figure 2 represents the data obtained by means of threefold coincidences. A total of 7000 coincidences were registered in 4000 hours. The thickness of the interposed lead was varied from 0 to 120 cm. We may see from Fig. 2 (full line) that when lead was placed only between the two lower tubes the intensity decreased rapidly until a thickness of 10 cm had been reached. We seem to detect the same decrease in the measurements

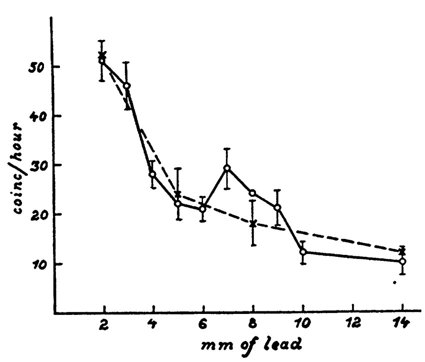

FIG. 1. Absorption of cosmic rays at 980 m depth in thin layers of lead between a twofold coincidence counter.

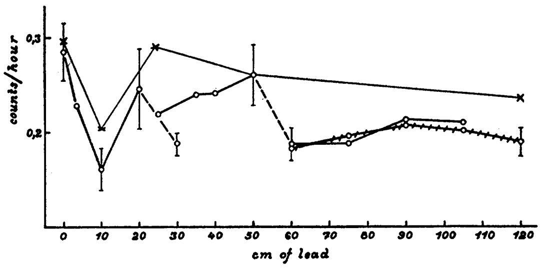

FIG. 2. Absorption of cosmic rays at 980 m depth in lead obtained with three counters. The line with crosses represents the measurements of V. C. Wilson. Full line: No lead between two upper tubes, varying thickness between lower tubes. Dotted line: 20 or 50 cm of lead between the center and bottom tubes; additional lead is placed between the upper tubes. Crossed line: 60 cm of lead between the top and center tubes, additional lead between the lower tubes.

performed by Volney C. Wilson[3] at 300 m water-equivalent depth, although he did not take into consideration the point at 10 cm Pb. In Fig. 2 we have drawn the curve corresponding to his measurements but have taken into account the point at 10 cm Pb; the two curves were adjusted at 50 cm Pb. If lead is placed between the top and center tubes, when 20 cm or 50 cm of Pb is in position between the lower tubes, the intensity again decreases considerably until an additional thickness of 10 cm has been placed between the upper tubes. (See dotted lines.) But if lead is placed between the two lower tubes when 60 cm Pb was between the top and center tube, the additional increase of lead between the lower tubes does not alter remarkably the intensity (crossed line).

In our opinion this behavior may be due to the following circumstances: great depth can be attained by an ionizing radiation (most probably mesotrons or perhaps protons) and by a non-ionizing radiation (neutrinos or neutrettos[4]). The greater the depth, the more important the non-ionizing component becomes and at 1000 m depth it may strongly exceed the number of the ionizing particles. The non-ionizing radiation produces along its path secondaries (photons, electrons) which give rise to a cascade shower. In this way the non-ionizing radiation is always accompanied, in a certain small percentage of its range, by ionizing particles and so it is able to discharge, but with small probability, the G-M

[1] J. Barnóthy and M. Forró, Nature **138**, 325 (1936); Zeits. f. Physik **104**, 744 (1937).
[2] J. Clay and P. H. Clay, Physica **2**, 1042 (1935) were the first to show that shower particles are to be found even at greater depth.
[3] V. C. Wilson, Phys. Rev. **55**, 6 (1939).
[4] N. Arley and W. Heitler, Nature **142**, 158 (1938).

tubes. If there is very little absorbing material between the tubes, one secondary is sufficient to produce a threefold coincidence. In this case, the penetrating ionizing and the non-ionizing radiation participate approximately equally in the production of the threefold coincidences. By putting several cm of lead above the bottom tube, the soft secondaries are stopped in it and now the non-ionizing ray needs two secondaries to be able to produce a threefold coincidence; accordingly the coincidence rate corresponding to the non-ionizing component will decrease to a small fraction of its original value. We will find the same behavior when lead is put above the center tube, no matter what thickness of lead is already between the center and the bottom tube, because now a non-ionizing ray is not able to discharge the two upper tubes with only one soft secondary. In a thicker layer of lead, however, the probability that a non-ionizing ray makes an encounter with a nucleus increases considerably and through transformations described by Heitler[5] or multiple processes discussed by Heisenberg[6] it can produce one or more heavy ionizing particles, which are able to penetrate through large thickness of lead. Here, we believe, lies the explanation of the increase of the intensity after the minima. In the second case, with 50 cm Pb between the lower tubes, the increase is less, as now only mesotrons of greater energy are able to discharge the apparatus.

The intensity variation corresponding to the crossed line should be attributed to heavy ionizing particles, most probably to mesotrons. It is possible that these mesotrons are created by non-ionizing particles, but in this case it is necessary to assume, that all of them have a range of several meters of lead, because the intensity does not decrease considerably between 60 cm and 120 cm Pb. This supposition does not seem to be likely. A second interpretation would be to assume that the non-ionizing radiation produces coincidences with the help of three soft secondaries. This seems unlikely too, because if the whole intensity should be attributed to a non-ionizing radiation, the rather small decrease up to 10 cm Pb (corresponding to a change from one to two secondary rays) would indicate that the non-ionizing ray is accompanied on half of its path by ionizing secondaries. The third explanation would be that these ionizing particles are primaries. It is true that a particle loses through ionization only approximately 4×10^{11} e-volts energy until it can attain 980 m depth. From the energy statistics of Blackett[7] we know that 2 percent of the rays to be found at sea level have a greater energy than 4×10^{10} e-volts. Assuming an energy distribution decreasing with the square of the energy, one can compute that 0.2 percent have greater energies than 4×10^{11} e-volts. This agrees well with the observation that the intensity at 980 m depth and with 120 cm Pb between the tubes was found to be only 0.15 percent of the total intensity at sea level. This explanation seems to be the most probable, even though for such great energies the radiative losses become appreciable[8] also for heavy particles.

We think that the most important question would be to determine the efficiency of the radiation at great depth when the thickness of the interposed lead absorber is very great (such measurements are now being made).

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[5] W. Heitler, Proc. Roy. Soc. **166**, 529 (1938).
[6] W. Heisenberg, Zeits. f. Physik **101**, 533 (1936).
[7] P. M. S. Blackett, Proc. Roy. Soc. **159**, 1 (1937).
[8] If it should be proved that this third explanation is right, our previous statement (Zeits. f. Physik **104**, 744 (1937)) namely that at great depth the number of the penetrating ionizing particles is to be neglected besides the number of the soft shower particles, must be amended.