Neutral Decay Products of Cosmic Radiation at Great Depth

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The absorption curve of cosmic radiation was measured during a period of seven years in a coal mine at a depth of about 1000 m w.e. The shape of the curve and the counter-efficiency measurements suggest that the most penetrating component of cosmic radiation consists of non-ionizing or scarcely ionizing rays. It was found that the intensity decreases for inclined directions less than it would correspond to the thickness of the material and its temperature coefficient is positive. All these experimental evidences, together with the known fact that at 400 m w.e. depth the exponent in the intensity *versus* depth variation changes from 1.8 to 2.8, favor the view that the radiation present at 1000 m w.e. depth is formed at the decay of the mesons in the atmosphere. Neutrini or neutral mesons may account for the findings.

IN the present paper we summarize the results obtained in the course of seven years at 700 and 1000 m w.e. (water equivalent) depth, respectively, in the coal mine of Dorog, situated at 35 km NW from Budapest. Surveying now these experiments it is evident that more ingenious experiments could have been thought of than those we actually carried out. But we started in 1936 quite unprejudiced with the observations and only slowly arrived at the conclusion that the radiation must consist of neutral decay products of mesons. Further, we should stress that we have measured absorption curves at depths where others could merely confirm the presence of cosmic radiation. The extremely small intensities necessitated very long series of measurements.

DESCRIPTION OF THE APPARATUS

The measurements were performed with a method published in 1933.[1] The first circuit consists of a back-coupled amplifier (Fig. 1) which substitutes the slow voltage drops occurring during a discharge on the wire of the G-M counter with an impulse having a high initial steepness of 10^{-8} sec. The substituted impulse starts instantaneously when the voltage of the wire drops by merely 30 millivolts. The circuit can be adapted to the quenching of G-M counters filled with pure gases. The quenching is already established through the capacity formed by the auxiliary grid and the control grid, but its action can be promoted by a coupling condenser connected between the points 4 and 6. The coincidences are selected in the usual Rossi manner with a common plate resistor and the coupling elements R C having a small time constant. A further back-coupled amplifier provides for sufficiently long impulses to operate a mechanical recorder. Only those details of the circuits will be here specified which are, according to our experience, important in measurements at great depth.

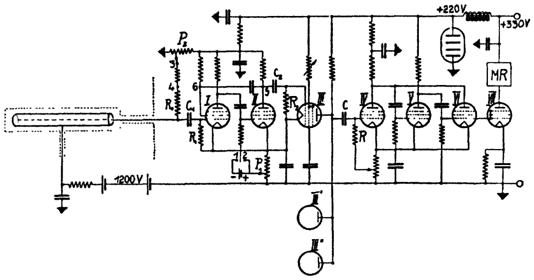

FIG. 1. Coincidence circuit.

The scarcely-ionizing nature of the radiation made it often necessary to register twofold coincidences, thus involving circuits with extremely high resolving power. However, on account of the slow motion of the electrons within the G-M counter, it is not safe to reduce for counters of 4 cm in diameter and argon+alcohol filling the resolving time below 10^{-6} sec.,[2] because otherwise more than ten percent of the genuine coincidences would be lost. For a coincidence time of 10^{-6} sec., however, the plate resistor of the valves *III*, *III'*··· is, contrary to the Rossi circuit, small with respect to the inner resistance of the vacuum tubes. This might cause a con-

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* Now at Barat College, Lake Forest, Illinois.

[1] J. Barnóthy, Naturwiss. **21**, 835 (1933).

[2] D. Nagy, Math. Fiz. Lapok **47**, 1 (1940).

siderable drop in the plate voltages even when only one of the valves is blocked. The selection of the coincidences is greatly facilitated if, for the valves *III*, *III′*, we use tetrodes without suppressor grids and make use of the secondary emission of the plates. If the potential of the screening grid is two to three volts higher than the plate voltage, a considerable secondary electron current will flow from the plate. When now one tube is blocked, it is sufficient that the plate voltage of the other tubes be raised by one to two volts in order to compensate the decrease of the plate current of the blocked tube through the decrease in the secondary currents from the plates of the other tubes.

Even if threefold coincidences are recorded, it is not advisible to choose the time constant of the coupling elements before the grid of valve *III* higher than 10^{-5} sec., because for the radiation observed at great depth the efficiency for twofold coincidences happens to be twenty times that of the threefold coincidences, in which case on account of the small total intensity a not negligible number of accidental coincidences might arise between the genuine twofold coincidences and the impulses of the third counter.

The theoretical resolving power of the circuit is limited by the ratio of the capacities of the electrodes and connecting wires to the steepness of the vacuum tubes. For resolving times up to 10^{-6} sec. commercial amplifier valves may be used. For other purposes when the utilizable resolving power is not limited by the use of gas-filled G-M counters, vacuum tubes with high steepness and small electrode capacities enable the extension of the resolving power to about 10^{-9} sec.

According to our measurements, a coincidence telescope in which every counter tray contains two G-M counters of 100 cm length, of 4 cm diameter, and filled with a mixture of argon+alcohol, when using for $R_0 = 100 M\Omega$ and a coincidence time $\vartheta = 1.4 \times 10^{-6}$ sec. the losses (listed in Table I) in the efficiency of the whole apparatus result on account of the slow reloading of the counter wires and on account of the coincidence time. The efficiency of our G-M counter for the radiation at sea level was better than 99 percent.

The high voltage of the G-M counters was supplied by a dry cell battery. The temperature within the locality during the whole year was within ±1°C constant. Consequently, an impulse-size regulator, commonly applied in our periodicity measurements, was here superfluous. Plate and filament storage cells, iron-hydrogen resistors and glow lamp stabilizers provided a constant voltage which did not appreciably drop even if the main electricity supply was switched off for several hours. The humidity in the mine amounted to 85–95 percent; consequently, waterproof boxes were used and the sensitive insulating parts of the apparatus were kept dry by heating or with P_2O_5.

TABLE I.

	Twofold coinc.	Threefold coinc.	Fourfold coinc.
On account of R_0	3%	4.5%	6%
On account of ϑ	6%	6 %	6%
Total loss	9%	10.5%	12%

The coincidences were recorded with a mechanical recorder and the distribution of the coincidences could be checked on a paper strap moved with constant velocity by clockwork.

MEASUREMENTS PERFORMED AT 730 m w.e. DEPTH

During two months of the year 1936 we measured at a depth of 730 m[3] two- and threefold coincidences in the positions illustrated in Fig. 2. The material immediately above the apparatus consisted of a coal layer. The arrangements *b*–*g* enabled us to determine the directional distribution of the radiation. The surface of the ground above the shaft was nearly level, the elevations nowhere exceeded 20 m, and with the help of a map giving the level lines in a ratio 1:25,000 and out of samples gathered from 30 different bores, we could establish the thickness and mass of the material above the apparatus for every part of

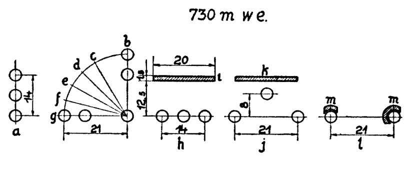

FIG. 2. Arrangements for the measurement of directional distribution and showers. Distances given in cm.

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

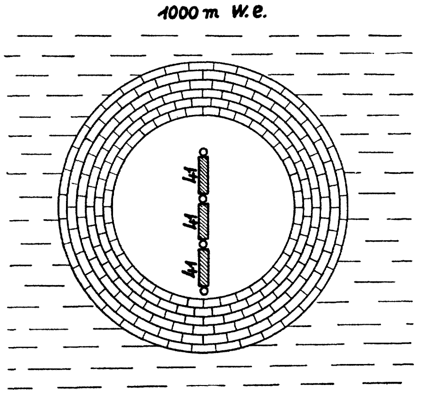

FIG. 3. Disposition of the counter-trays within the brick cylinder of the shaft.

its aperture with nearly as much accuracy as if the whole device had been submerged in water.

For the directional distribution we found (after subtracting as residual intensity that of position *g*):

$$D(\alpha)\times 10^{6} = -0.2+3.7\cos^{2}\alpha-1.0\cos^{4}\alpha \quad \text{coinc./cm}^{2}\text{ hours, square degree.}$$

The vertically incident radiation computable from this directional distribution yields the value:

$$J_v = 2.5\times 10^{-6}\ \text{coinc./cm}^{2}\text{, hours, square degree.}$$

In all these measurements carried out deep underground below a dense material, the intensity due to cascade showers initiated by decay electrons of the mesons is negligible, merely knock-on secondaries and their cascade showers have to be considered. According to the computations of Bhabha,[4] the probability that a primary meson or proton of, say, $10^{11}-10^{12}$-ev energy should be accompanied by more than two secondary particles is in lead twice as much as in lighter materials, for instance, in coal. Therefore, we should have to expect that putting above a shower arrangement lead layers, the intensity would increase by a factor 2, whereas the observations in positions *i* and *k* with 1.5 cm Pb above the G-M counters indicate that with lead layer the intensity amounts merely to 40 percent of the intensity without lead. This suggests that the primary radiation cannot consist of mesons or other heavier charged particles.

From the measurements made in positions *l* and *m*, where twofold coincidences were registrated between horizontally placed G-M counters, first without lead and then with the counters surrounded by 1.5 cm Pb, we may reckon the range of the secondary particles to be 19 g/cm². This value is smaller than the range of the secondaries found with the same arrangement under a coal layer in our institute (48 g/cm²). The range of these secondaries establishes with sufficient certainty that the showers observed in the mine do not consist of coherent rays, able to penetrate through the deep earth layer.

A further noteworthy feature of the radiation is that the ratio of the horizontal intensity, i.e., of the shower intensity to the vertical intensity, is greater by a factor 4–6 in the mine than in our institute (120 m above sea level) under a coal layer. The arrangements *l* and *j* were able to detect showers with two to three particles. Assuming that the intensity from the horizontal direction is almost negligible, that the showers have the same directional distribution as the vertical radiation and, moreover, that the ratio of showers with three particles to those with two particles has the same value as the ratio of the showers containing two particles to those with only one particle, we can reckon from the respective counting rates the intensity of the shower particles arriving from the vertical direction to be:

$$J_s = 2.6\times 10^{-6}\ \text{coinc./cm}^{2}\text{, hour, square degree.}$$

The amazing equality of this value of J_s with that of the vertical intensity J_v, together with the foregoing considerations, suggest that in the mine the penetrating radiation consists of non-ionizing rays, which are able to produce coincidences with the help of their ionizing secondaries. However, the secondaries and cascades can not be produced by knock-on electrons, but in nuclear collisions. This explains the fact that the number of secondaries decreases when the material above a shower arrangement is replaced by a material of higher atomic weight. At that time we assumed that the penetrating non-ionizing component consisted of neutrini created in air showers.

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[4] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1928).

RADIATION MEASURED WITH TWOFOLD COINCIDENCES

In the subsequent measurements which we began at the end of 1937 at 1000 m w.e. depth, the apparatus was installed in a cylindrical side gallery of the mine (Fig. 3), which had a diameter of 2 m; it had a brick casing 60 cm thick. In every counter tray two parallel-connected G-M counters were mounted; thus the sensitive area was increased to 820 cm^2 and provision was made to place 120 cm of lead between the counter trays.

Suspecting the non-ionizing nature of the penetrating radiation, our aim first was to measure the efficiency of the radiation by determining the twofold and threefold coincidence rates. Table II contains the results. In case of the twofold coincidences it was important to determine separately the rate of accidental+shower coincidences. This was performed by placing the two counters in a horizontal plane as far apart as the narrow locality permitted, a huge lead block being placed between the counters. The number of accidental coincidences was computed from the coincidence time of the circuit to be 1.4 coinc./hour; in horizontal position we found 5.6 coinc./hour, thus 4.2 coinc./hour were due to showers.

For the ratio of the threefold to twofold coincidences we found the very low value of 4.7 p.c. The gas-filling of the G-M counters was equivalent to about 1 cm of air at N.T.P.; thus this radiation which is hardly able to produce a threefold coincidence has a specific ionization of 0.05 ion/cm air at N.T.P. G-M counters of 4 cm in diameter have, according to our measurements, 0.4 p.c. efficiency in detecting γ-rays from RaC. Although the specific ionization of the radiation exceeds the value we found for γ-rays, we can not discard the possibility that perhaps the apparent greater specific ionization is a consequence of the fact that it is able to create more energetic electrons. In order to investigate this point we have placed 11 cm of lead between the counters (second row in Table II), the efficiency was again very low, only 10 p.c., meaning that after 11 cm Pb this scarcely ionizing radiation is still present. This circumstance excludes its interpretation as being a γ-radiation. In this second set we have subtracted from the number of the twofold coincidences merely the number of the accidental coincidences, the number of the showers being now negligible, since the bottom counter was shielded from all sides by lead.

TABLE II.

Absorber	Distance of the counters	Twofold coinc. per hour	Threefold coinc. per hour	Efficiency
0.4 cm Pb	24 cm	26.6±0.4	1.25±0.11	4.7 p.c.
11 cm Pb	24 cm	11.0±1.4	1.09±0.10	10 p.c.

The result that the intensity of the twofold coincidences decreases rapidly with absorber thickness whereas the intensity of the threefold coincidences does not, seems to indicate that two kinds of penetrating radiation are present at 1000 m depth—one, scarcely ionizing and not able to produce a threefold coincidence, and another which gives rise to the threefold coincidences and which may be perhaps ionizing. Anyway, from the very slight decrease in the number of the threefold coincidences after inserting 11 cm Pb, we may infer that this radiation is also penetrating and moreover it cannot consists of electrons.

The properties of the scarcely ionizing radiation which is not able to produce a threefold coincidence were investigated by inserting thin lead layers between the counters of a twofold coincidence device. Lead blocks placed at both sides of the counters sufficiently insured the triggering of the counters by shower particles.

The intensity decreases rapidly (Fig. 3), indicating that the scarcely ionizing radiation has a high absorbability in lead. However, after a

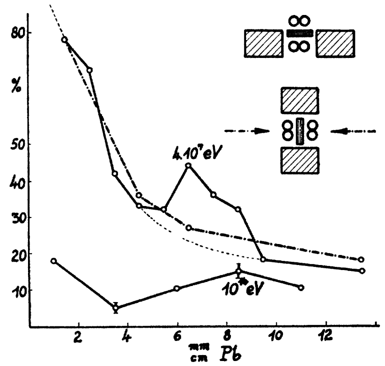

FIG. 4. Absorption curve of twofold coincidences in lead. For the upper curve the abscissae are expressed in mm Pb, for the lower curve in cm Pb.

TABLE III.

Absorber	Distance of the counters	Threefold coinc. per hour	Fourfold coinc. per hour	Efficiency
3 cm Pb	152 cm	0.099 ±0.008	0.087 ±0.009	88 ±10 p.c.
123 cm Pb	152 cm	0.088 ±0.009	0.058 ±0.008	66 ±10 p.c

minimum the intensity increases anew, reaches a maximum, whereafter it falls down. This part of the curve is very similar to the Rossi curve of showers, and obviously the absorption of the scarcely ionizing radiation is also due to the production of electron pairs and cascade showers.

The most striking thing, however, is that the absolute intensities and the slope of the absorption curve remains unchanged when the whole arrangement is turned through 90°, in which case only the incident rays coming sideways are able to trigger the counters. In Fig. 4 the dash-dot (–·–·–) line corresponds to this measurement. This result can be interpreted by assuming that the scarcely ionizing radiation is isotropic for the whole hemisphere. At first glance we might interpret this phenomenon by saying that the radiation is produced when secondary mesons stopped in the surrounding material suffer decay. This explanation is, however, not consistent with the small range and relatively high intensity of the scarcely ionizing radiation as compared to the small intensity of the secondary mesons. (See ratio of two-fold to three-fold coincidences). Anyhow, the isotropy of the radiation does not invalidate the previous findings of a directional distribution in our 1936 measurements, because then three-fold coincidences were recorded, thus not the directional distribution of this soft, scarcely ionizing component.

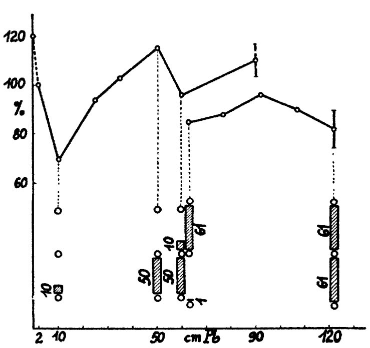

FIG. 5. Absorption curve of threefold coincidences in lead. Lead thickness varied either between bottom and middle counter, or between middle and top counter.

The measurements were extended for lead thicknesses up to 14 cm Pb; the lower curve in Fig. 4 indicates the results. The two curves were adjusted for the intensities at 1 cm Pb. The abscissa for the lower curve indicates thicknesses in cm Pb. Again the intensity decreases and has a subsequent increase. Very thin and moderately thick lead layers seem to provoke similar intensity variations. Therefore, it is very probable that at least two kinds of scarcely ionizing components are present, the first being absorbed in about 5 mm Pb, the second in about 5 cm Pb. If the absorption is due to cascade production, we may compute from the position of the maxima, in accordance with the cascade theory, the initial energy of such a shower: $l_{\max}=\ln(E/E_i)$. ($l_{\max}$ measured in radiation units $=0.5$ cm, and $E_i=10^7$ ev for lead.) From the upper curve we find $E=4\times10^7$ ev and from the lower curve $E=10^{14}$ ev. Hence the first scarcely ionizing component is much softer than the radiation producing the usual cascade showers at sea level. Whereas the high value for the second component renders it very improbable that this component should create electron showers, these secondaries must consist of heavier particles, obviously mesons.

RADIATION MEASURED WITH THREEFOLD COINCIDENCES

Our next purpose has been to determine the nature of the penetrating component giving rise to threefold coincidences. In case this component should consist of ionizing particles we might not expect to find a difference in the four- and threefold counting rates. Table III indicates the results. With 3 cm Pb between the counters, three of the four G-M counters were already shielded by 1 cm Pb. Thus it seems very likely that the number of the shower coincidences is, in both arrangements, negligible. The total efficiency difference between a threefold and a fourfold arrangement is, according to Table I, two p.c. The observed efficiency for the additional fourth G-M counter was with 3 cm Pb 88 p.c., a value equal to that found with the same arrangement in our institute. This apparently low efficiency is due to the fact that threefold coincidences are more likely to respond to showers than fourfold coincidences. Hence, if 120 cm Pb were inserted between the counter trays, the efficiency decreased to 66 p.c. although now the thick lead layer excluded any effect of showers. This result indicates that the penetrating component cannot consist of ionizing particles alone. In order to investigate the nature of this component we measured its absorption in lead. In the upper curve of Fig. 5 lead was first placed gradually between middle and bottom counter and only when 50 cm Pb were reached was the additional lead placed between middle and top counter. The intensity decreases in the first 10 cm Pb very rapidly after passing through a minimum the intensity increases anew to reach nearly its original height after 30 cm Pb. A second drop is only observable when the additional lead was placed between top and middle counter. The shape of this absorption curve can in no case be explained by an ionizing radiation alone; we have rather to assume that a non-ionizing agent creates in the material above the apparatus, in clay, secondaries of about 10 cm Pb range. If less than 10 cm Pb are inserted, it can produce a discharge in all the three counters, whereas for greater lead thicknesses it can only discharge the two upper counters and consequently we observe a decrease of intensity. The creation of a further secondary in lead is now required for the production of a threefold coincidence. The number of the secondaries created in lead will increase with the thickness of the lead layer. Accordingly, the intensity increases for greater thickness. A second drop will occur when lead is placed between top and middle counter, because now a secondary created in clay, which was able to trigger both of the upper counters, is prevented from reaching the middle counter. A threefold coincidence can only occur when the non-ionizing radiation liberates a secondary ray above each of the counters. With the thickness of the upper layer, the number of the secondaries triggering the center counter increases, and a further rise in the intensity might result.

On the other hand, in the lower curve of Fig. 5, when 60 cm Pb was placed permanently between top and middle counter and only the thickness of the lead layer between middle and bottom counter was varied, we may remark that the intensity remains fairly constant.

TABLE IV.

Number of coinc.	Time in hours	coinc./ hour	Lead in cm	Intensity ±p.e.	
420	1648.2	0.245	2	100±3.4 p.c.	M_0
230	1125.7	0.191	7	78±3.7	
311	1665.6	0.175	12	71±2.9	m_1
273	1348.8	0.209	17	85±3.4	
268	1292.0	0.223	22	91±3.5	M_1
259	1402.9	0.200	27	82±3.2	
310	1613.1	0.182	32	74±2.7	
399	2012.9	0.187	37	76±2.7	
325	1916.9	0.164	42	67±2.6	m_2
294	1535.7	0.180	47	74±3.1	
306	1584.6	0.182	52	74±3.0	
126	592.3	0.209	57	85±5.2	M_2
254	1232.3	0.191	62	78±3.6	
191	918.5	0.185	67	76±4.2	
48	309.8	0.139	72	57±6.1	
50	334.8	0.137	77	56±5.8	m_3
145	1000.3	0.139	82	57±3.3	

Two interpretations can be offered for this behavior. Either the residual intensity after 60 cm Pb is due to an ionizing radiation, the non-ionizing radiation being stopped in 60 cm Pb—a circumstance which is highly improbable for a radiation which was able to penetrate 1000 m w.e.—or the lower lead absorbs about the same amount of secondaries arising from the upper lead block as are created in it anew.

After a short interruption the measurements were resumed in 1939 and were continued till wartime activities put an end to the whole enterprise. Unfortunately, our whole apparatus was destroyed during the siege. The only difference as compared to the previous sets was that now we placed simultaneously the same amount of lead between top and middle counters as between middle and bottom counters. Our aim was to determine with sufficient accuracy the exact shape of the absorption curve. Therefore, every point of the curve was measured several times. A total of 4209 coincidences were recorded in 21,734 hours. (In one of the series 70 cm of wood were placed above the counter trays.[5] However, it was seen later that this circumstance did not affect the results.) The data are collected in Table IV. The values of the intensity are corrected for a mean temperature of 6°C with a temperature effect of 1.0 percent per degree C.[6]

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[5] J. Barnóthy and M. Forró, Zeits. f. tech. Physik **21**, 290 (1940); Phys. Rev. **55**, 870 (1939).

[6] M. Forró, Phys. Rev. **72**, 868 (1947).

TABLE V.

Max. – Min.	Intensity differences
$M_0 - m_1$	29±4.5 percent
$M_1 - m_1$	20±4.5
$M_1 - m_2$	24±4.3
$M_2 - m_2$	13±3.9
$M_2 - m_3$	23±3.9

The differences between the maximum and minimum points are collected in Table V. For M_2 we used the mean intensity of the two arrangements with 57 and 62 cm Pb, because in the maximum position (57 cm Pb) less than 200 coincidences were recorded and further, since the intensity was practically constant for the last three points, we used for m_3 the mean of all three values. Except for $M_2 - m_2$ in all other cases the intensity differences are greater than four times their probable error, and even in this latter case it is 3.3 times its error. Thus in the intensity variation the existence of two minima and two maxima can be seen.

INTERPRETATION OF THE ABSORPTION CURVE

The shape of this absorption curve cannot be interpreted by assuming an ionizing radiation. In order to obtain an analytic representation of the curve, let us assume that (1) the non-ionizing radiation produces secondaries of sharp range $=a/2$ in clay and of range $=a$ in lead (this proportion of the ranges was taken for the sake of simplicity); and (2) the probability of a secondary being produced along dx either in the material above the counters, or in the absorber between the counters, is dx/P, where P is the mean free path between the production of two such secondaries expressed in mass units. For the sake of simplicity let us assume that P is identical for clay and lead. We choose unit of length $=P$ and further $P=1$. The counters are separated by distances x.

If $x>a$, a threefold coincidence takes place whenever at least one secondary is produced in each of the three intervals of length $a/2$, or a, above or between the counters. For $x<a$ the intervals overlap and a coincidence may be caused by less than three independent secondaries. In particular for $x=0$ one secondary is sufficient to give rise to a coincidence.

TABLE VI.

Interval	dJ/dx
I. $0<2x<a/2$	$-2e^{-a/2}e^{-x}$
II. $a/2<2x<a$	$2e^{-x}(e^{-x}-e^{-a/2})$
III. $a<2x<2a$	$(1-e^{-a/2})e^{-x}(1-2e^{-x})$
IV. $2a<2x$	0

When x increases from 0 to a, we have to deal with four cases. The probability computations[†] yield the derivatives given in Table VI of the intensities within the respective intervals: Within interval *I* the intensity decreases; in *II* the intensity increases, reaches a maximum for $2x=a$; furthermore, a minimum must occur at the intersection of the intervals *I* and *II*, i.e., for $2x=a/2$; in *III* we find a minimum for $e^{-x}=0.5$ and in interval *IV* the intensity remains constant for all values of $x>a$.

We may infer that this theoretical curve is qualitatively in agreement with our experimental curve of Fig. 6 (except for the last decrease of intensity). The place of the first minimum (m_1) corresponds to the range of the secondaries created in clay; the first maximum (M_1) will occur when the total thickness of the two lead layers is equal to the range of the secondary produced in lead, and the second maximum (M_2) is reached when the thickness of each lead layer is equal to the range of the secondary created in lead. We conclude that the experimental curve can be obtained by assuming that a non-ionizing radiation produces ionizing secondaries in the material above the counters and in the absorber between the counters. In particular, it is necessary to assume secondaries of about 10 cm Pb range in clay and of 20 cm Pb range in lead. The secondaries must therefore be heavier particles, probably mesons.

The circumstance that the range of the secondary ray created in clay is smaller than the range of those created in lead can be interpreted by assuming that nuclear forces are responsible for the production of these secondaries. However, on account of the short range of nuclear forces the interaction will actually take place merely with the nucleons situated in the vicinity of the track of the penetrating, non-ionizing component. The

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[†] We are indebted to L. Jánossy for a helpful discussion of this analysis.

total energy of the created meson is equal to the whole energy transferred to the nucleus. In a first approximation the number of the nucleons encountered by the non-ionizing radiation during its path through the nucleus is equal to $8N^{\frac{1}{3}}$ (N=atomic weight). Therefore, the mesons produced in clay will receive about half as much energy as those created in lead. A meson of range 10 cm Pb can be created with a total energy (rest energy+kinetic energy) of 3.4×10^8 ev, and if its range is 20 cm Pb, with 6×10^8 ev, these values being in the expected ratio. Every nucleon will receive about 10^7-ev energy.

In order to interpret the last decrease of the intensity after M_2, we have either to assume that the penetrating non-ionizing radiation is absorbed in 80 cm of lead, a circumstance which is—as we already mentioned—highly improbable, or the mechanism of the creation of secondaries is more complex than assumed hitherto. Perhaps according to the way the collision between non-ionizing radiation and atomic nuclei takes place, two or more kinds of secondaries with different ranges are produced in the different materials (clay, lead).

In our interpretation of the absorption phenomena we have hitherto only dealt with the two ionizing secondaries of 10- and 20-cm Pb range, created by the penetrating non-ionizing radiation in clay or in lead. A full understanding would, however, require taking into consideration the effect of the scarcely ionizing radiation. As seen, its intensity is 21 times higher in producing twofold coincidences than in threefold coincidences, suggesting the probability that it would discharge a single G-M counter is 450 times as great. Should this scarcely ionizing component be a permanent companion of the penetrating non-ionizing radiation, we would have to take into account, in interpreting the absorption curve, that the top counter tray and the counter in the middle for small lead thicknesses are almost always triggered by this component. At present, however, we have far too little experimental knowledge of its properties to be able to carry out such a quantitative analysis of the absorption curve.

INTENSITY *VERSUS* DEPTH VARIATION

Some light is cast upon the nature of the penetrating radiation by considering the intensity-depth dependence. According to the measurements of Ehmert,[7] Clay,[8] and V. C. Wilson,[9] the intensity decreases between 40 and 250 m w.e. inversely proportional to the 1.8 power of the depth; for still greater depth the exponent changes to 2.7. Represented on a logarithmic scale we may observe a bend at about 300–400 m w.e. The intensity variation before the bend corresponds, as known, to a meson intensity with an integral spectrum proportional to $E^{-1.7}$.

To explain the bend, we might think that the greater absorption below of thick layers is due to the circumstance that for such energies the radiative losses become more and more important. However, according to the cascade theory, only for a meson of 2.5×10^{12}-ev energy will the energy loss due to ionization be of the same order as the radiative loss. On the other hand, if only ionization losses are to be considered, a meson of 2×10^{11} ev would be able to reach a 500-m depth. Consequently, the bend of the absorption curve can not be explained by radiative losses. Since there does not seem to exist any reason preventing a meson of 2×10^{11} ev to reach 500 m, and nevertheless the intensity at 500 m does not correspond to a meson intensity, we infer, that in the primary meson spectrum, for reasons unknown hitherto, mesons with greater energies than 2×10^{11} ev are not present. (In a paper dealing with the origin of cosmic radiation,** we obtained the following expression for the integral

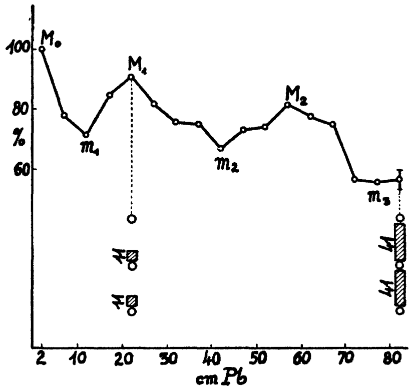

FIG. 6. Absorption curve of threefold coincidences in lead. Lead thickness varied simultaneously at both places.

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[7] A. Ehmert, Zeits. f. Physik **106**, 751 (1937).

[8] J. Clay and A. Gemert, Physica **6**, 497 (1938).

[9] V. C. Wilson, Phys. Rev. **53**, 337 (1938).

** T. Barnóthy and M. Forró, Csill. Lapok **7**, 65 (1944).

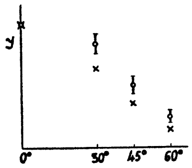

FIG. 7. Intensity found for various inclinations. o indicates the experimental values and × the values corresponding to the thickness of the material.

spectrum of fast mesons:

$$F_m = 2.3\times 10^{-4}[(e^{-3W}/3W) - Ei(-3W) + 2Ei(-6W)],$$

where the energy is expressed in $W = E/2\times 10^{11}$-ev units, and Ei denotes the exponential integral. This expression can account for the cut-off of the energy spectrum at about 2×10^{11} ev.)

Let us assume that the depth below 300 m w.e. is only reached by decay products of mesons and, further, that these decay products have constant energy losses. In this case the intensity will be proportional to the number of mesons disintegrated in the atmosphere:

$$J_D = \int_{E_{\min}}^{E_{\max}} \frac{J_0}{E^{2.7}}\left[1 - \exp\left(-\frac{L\mu c^2}{c\tau E}\right)\right] dE \sim \frac{\text{const}}{E_{\min}{}^{2.7}} = \frac{\text{const}}{H^{2.7}},$$

(L = mean free path of the meson; μ = its mass; τ = its lifetime and H = thickness in w.e.). For all energies to be considered the exponent is small compared to 1, and we may develop in power series and neglect the higher terms. As seen, the above result is in good accordance with the experimental findings.

DIRECTIONAL DISTRIBUTION OF THE RADIATION

A further circumstance favoring the view that only decay products are present at great depth is furnished by the comparison of the directional distribution of the radiation at sea level with that at 730 m depth. At sea level we found with a counter telescope with aperture 10° in zenith-angle directions from a total of 4 million coincidences:***

$$D(\alpha)\times 10^4 = 5.0 + 74.5\cos^2\alpha + 0.5\cos^4\alpha \quad \text{coinc./cm}^2\text{, hour, square degree,}$$

corresponding to

$$D(\alpha) \sim \cos^2\alpha.$$

For inclined directions the thickness of the material varies according to $1/\cos\alpha$. We should, therefore, expect to find a meson intensity varying like $E^{-1.7}$, i.e., a variation according to $\cos^{1.8}\alpha$. However, on account of the fact that in inclined directions the path of the mesons increases, the decay of the mesons will render the intensity decrease somewhat steeper. Actually it was found to vary like $\cos^2\alpha$.

At 730-m depth we found for the directional distribution[3]

$$D(\alpha)\times 10^6 = 0.2 + 3.7\cos^2\alpha - 1.0\cos^4\alpha \quad \text{coinc./cm}^2\text{, hour, square degree.}$$

Hence,

$$D(\alpha) \sim \cos^{1.7}\alpha.$$

At first glance this slight difference in the exponent of the cosine seems to mean that the effect of the decay is less important for these more energetic mesons present at great depth. Consequently, we should infer that both directional distributions have to be attributed to the same kind of radiation, i.e., to mesons. However, according to the experimental data, at 730 m depth the intensity decreases with the −2.7 power of the depth, accordingly we should expect a directional distribution varying with $\cos^{2.7}\alpha$ instead of the actually found $\cos^{1.7}\alpha$.

Let us try anew to assume that great depth is only reached by decay products of mesons. Writing as before:

$$J_D = \int_{E_{\min}}^{\infty} \frac{\text{const}}{E^{2.7}}\left[1 - \exp\left(-\frac{L\mu c^2}{c\tau E}\right)\right] dE = \text{const}\frac{L}{E_{\min}{}^{2.7}}.$$

For inclined directions the thickness of the material varies like $1/\cos\alpha$ and similarly $E_{\min}$ varies with $1/\cos\alpha$. But also the length of the trajectory L of the meson in the atmosphere is varying like $1/\cos\alpha$. Hence

$$J_D = \text{const}\times\cos^{1.7}\alpha,$$

in best accordance with the observed variation.

*** T. Barnóthy and M. Forró, unpublished results. See also Nature **144**, 116 (1939).

THE ABSORPTION ANOMALY FOR INCLINED DIRECTIONS

The circumstance previously mentioned that in this particular shaft the thickness of the earth layer above the apparatus was known with great accuracy enables us to compare directly the intensities we measured with inclined counter telescopes with the results of V. C. Wilson[9] obtained with a vertical apparatus. For the sake of an exact computation we have divided the aperture of our counter telescope into 16 parts of equal length and have reckoned for every center line of these parts the mass of the material above it. Considering also the variation of the sensibility for rays striking the counter telescope at different angles, we could compute the intensities we should have found at different inclinations according to Wilson's measurements. In Fig. 7 the crosses correspond to the values computed from Wilson's observations and the circles to our actually found intensities. We may remark that in every inclined direction the directly measured intensity is higher than would correspond to the thickness of the material, meaning that at great depth the absorption anomaly has a reversed sign: the intensity decreases less than would correspond to the thickness of the layer. This peculiar behavior may be easily understood if we take into account that in inclined directions the mean path of the meson in air is longer, a greater number of mesons suffer disintegration, more decay products are formed; accordingly, the intensity of the decay products will be higher than would correspond to the thickness of the material.

This inverse absorption anomaly can be detected in Wilson's results. At several depths he measured with inclined counter telescope and observed that in all cases the intensity values did not fit his absorption curve, but were always higher. To account for this discrepancy Wilson assumed that the true mean thickness of the material did not correspond to that measured in the direction of the center line of his apparatus, but to thicknesses in directions tilted 7° less than the center line. He argued that on account of the breadth of the aperture of his telescope the surplus from directions above the center line exceeds the loss due to the greater thickness of the absorbing layer for more inclined directions. Although his argumentation is substantially correct, closer scrutiny reveals that the corrections to be applied are in each case much smaller than assumed by Wilson: for 45° inclination the correction is less than $\frac{1}{4}$ degree and even for 72° it amounts merely to one degree.

In Fig. 8 the crosses indicate in polar coordinates the intensities corresponding to the same thickness of material when measured with a vertical apparatus, the circles indicate the intensities actually measured by Wilson, and the squares the intensities we obtain if we take into account that the number of the decay products is, in consequence of the increased path of the mesons, greater for inclined directions.

POSITIVE TEMPERATURE EFFECT

Still another circumstance supports the view that only decay products of mesons are present at great depth. One of us[6] has found that a positive temperature dependence exists for the radiation present at 1000 m w.e. depth. The data collected during the investigations of the years 1939–43 were suitable for such an analysis, since it was possible to select nine different arrangements where observations were performed at the same place and with identical thickness of lead. However, they were repeated on three different occasions and each time the measurements were carried on for at least two–three weeks. For every arrangement the correlation between intensity and outer air temperature was computed. Although the individual values of the temperature effect have, on account of the small intensities, large standard errors, the mean value of these

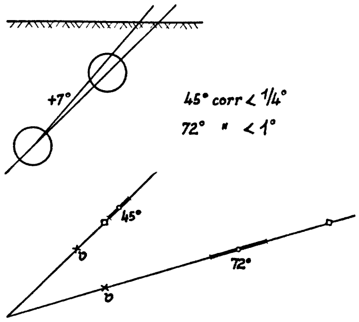

FIG. 8. Intensities for 45° and 72° inclination of the counter telescope. o is the measured values of Wilson, × the intensities corresponding to the thickness measured vertically and □ after correcting for greater number of decay-products in inclined directions.

nine individual results yields an effect:

$$+0.74\pm0.13 \text{ percent per degree C},$$

a value exceeding six times its probable error, and therefore the existence of a positive temperature effect is established.

As known, the temperature effect of cosmic radiation at sea level has a negative sign—the rise in temperature tends to diminish the intensity. Blackett[10] offered an interpretation for this behavior by assuming that at higher temperature the atmosphere expands and the place where the mesons are produced is shifted upwards. Consequently, a larger number of mesons disintegrate before reaching sea level; the intensity will be lessened. Pursuing this argumentation we may infer that with higher temperature more decay products are formed. Accordingly, their intensity increases and we will observe a reversed, i.e., a positive, temperature effect for the decay products.

CONCLUSIONS

a. The shape of the absorption curve and the counter-efficiency measurements indicate that below 730 m w.e. depth the cosmic radiation consists—at least to a great extent—of non-ionizing or scarcely ionizing particles.

b. Three independent experimental evidences, namely, (1) the intensity *versus* depth variation, (2) the inverse absorption anomaly, and (3) the positive temperature effect, favor the view that great depth is reached merely by decay products of mesons.

The next question seeking an answer is to establish the nature of these non-ionizing decay products. Fast mesons might disintegrate into protons and neutrons. However, according to the theory of Hamilton, Heitler, and Peng,[11] only neutrons with extremely high energies (10^{14} ev) would be able to reach 1000 m depth. Conversely, the intensity *versus* depth variation indicates that if no mesons of higher energy than 2×10^{11} ev are present in the primary meson spectrum, no neutrons of the required energy can be formed.

The other alternative at our disposal is that the meson disintegrates into an electron and a neutrino. Several considerations seem to suggest that it is more likely that a meson of integer spin, 212 m_0 mass, and 2.17×10^{-6} sec. lifetime would disintegrate in the atmosphere into an electron and a "meso-neutretto." The latter neutral particle would have $\hbar/2$ spin, about 10^{-10} sec. lifetime, and 97 m_0 or $148m_0$ mass.[12]

To date we know theoretically far too little about neutrini and neutrettos and their possible interactions to be able to perform a more exact computation. We think it is up to the theoretical physicist to find significant differences in the behavior of neutretto and neutrino radiations, which would indicate a way to check this point experimentally and thus solve the problem of the nature of the penetrating component.

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[10] P. M. S. Blackett, Phys. Rev. **54**, 973 (1938).

[11] Hamilton, Heitler, and Peng, Phys. Rev. **64**, 78 (1943).

[12] T. Barnóthy, Phys. Rev., in print; Nature **161**, 681 (1948).