On Some Low Ionizing Radiation Observed by Measurements of Cosmic Radiation at Great Depths

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By measurements of twofold, threefold, and fourfold coincidences with a Geiger counter telescope, the underground rays at 660 and 540 m w.e. (water equivalent) have been divided into two components. One of the components is ionizing, discharging the counters with almost 100 percent efficiency, and has a strong maximum in the vertical direction. The other component discharges the counters with a very low efficiency, producing numerous twofold coincidences but practically no threefold or fourfold coincidences. It is isotropic in direction and rapidly absorbed in lead. This second component is thought to be composed of γ-rays of local radioactive origin. The telescope used in these experiments differed from that of Barnóthy and Forró in that it was protected from side showers by anticoincidence counters. The ratio of twofold to threefold coincidences was found to be about 1.4 instead of 20 as reported by Barnóthy and Forró at 1000 m w.e.

THE PROBLEM OF GREAT DEPTHS

As concerns the problem of cosmic radiation reaching great depths (some hundred m w.e.), it is assumed by most physicists that this radiation is a meson radiation (perhaps with some admixture of protons) accompanied by knock-on electrons, and cascade showers started by these.[1] Quite different views on this subject are given by Barnóthy and Forró[2] who assume that at depths greater than 500 m w.e. it is mainly non-ionizing radiation produced by the decay of μ-mesons which penetrates there. They consider that our instruments at those depths are operated by secondaries of that non-ionizing radiation.

These differences in views are derived from some anomalies observed by measurements of cosmic radiation at great depths. The best known anomaly is that giving the relation between the intensity of cosmic radiation and the depth. If we take the integral spectrum of mesons as given by the relation: $J=cE^{-\gamma}$, and we also take the losses of energy of mesons to be proportional to the depth H which they have traversed, we obtain the relation: $J=cH^{-\gamma}$. Now taking into account the experimental results, in the diagram $\log J$ *versus* $\log H$ we get a line which is broken at about 300 m w.e.[3] Up to 300 m w.e. we have the relation: $J=cH^{-1.8}$, and beyond that depth the exponent changes from the value 1.8 to 2.8.

Lyons[4] considers an additional loss of energy of very energetic mesons by radiation as a cause of this change of dependence of the intensity on the depth. That loss must be accentuated below 300 m w.e. A closer analysis of this process proves that the losses of energy suffered by mesons which have traversed such depths are too small to explain this phenomenon.

There are now in the literature of the subject two opinions[2, 5] on this problem based on a similar assumption of meson decay. The introduction of meson decay influences the shape of the spectrum of the radiation at great depths. The mean range of decaying mesons is proportional to the energy. Then in the spectrum of decay products we shall have a lack of particles of the highest energies and this should be observed for energies for which the mean range of mesons is equal to or greater than the height at which mesons are produced in the atmosphere. In the spectrum of decay products of the form $E^{-1.8}$, we get the factor E^{-1} which explains the dependence observed, i.e., $J=cH^{-2.8}$, if we assume that all the radiation at great depths is produced by decay products of mesons. The main difference between Barnóthy and Forró and Greisen is that Barnóthy and Forró assume that at great depths we observe the neutral products of μ-meson decay, Greisen on the contrary introduces into this problem the process of the decay of π-meson into μ-meson. He evaluates in this way the energy by which the spectrum changes from the form $E^{-1.8}$ to $E^{-2.8}$. This energy ($E\approx 10^{11}$ ev) is necessary for the meson to traverse some hundred m w.e. With this supposition it is not necessary to consider the cosmic radiation at great depths to be composed of neutral meson-decay products. The μ-mesons themselves are decay products.

But Barnóthy and Forró in the paper mentioned report among many interesting results also a phenomenon which they interpret as an argument for the opinion that at great depths we have to do especially with neutral meson-decay products. This phenomenon, mentioned in 1939,[6] was communicated at the Cracow Cosmic Rays Conference in October 1947. They observed at the depth of 1000 m w.e. that the radiation there measured was able to give many times more double than threefold coincidences in the same telescope. The ratio of threefold to double coincidences in their measurements was 0.05. Barnóthy and Forró express the opinion that this phenomenon proves the existence at great depths of a scarcely ionizing component of cosmic radiation. For this component the

[1] V. C. Wilson and D. J. Hughes, Phys. Rev. **63**, 161 (1943).
[2] J. Barnóthy and M. Forró, Phys. Rev. **74**, 1300 (1948).
[3] J. Clay and A. V. Gemert, Physics **VI**, 497 (1939).
[4] D. Lyons, Physik. Zeits. **42**, 166 (1941).
[5] K. Greisen, Phys. Rev. **73**, 521 (1948).
[6] J. Barnóthy and M. Forró, Phys. Rev. **55**, 870 (1939).

probability of threefold coincidences ought to be smaller than that of double ones.

The aim of this work, of which we are giving the provisional results in this paper, was to check this interesting phenomenon and to investigate more closely the properties of the radiation which produces it.

DESCRIPTION OF THE APPARATUS

Our measurements were performed in the salt mine at Wieliczka near Cracow. The deepest level at our disposal was 282 m below ground. The layers above the telescope consisted of rocksalt, sandstone, gray slit, and silt with grains of rocksalt, gypsum, and anhydrite. The water equivalent was estimated from samples taken from different layers at different levels. The measurements were carried out in horizontal passages (about 2 m high) in the salt layers at two levels, 660 and 540 m w.e. The work in the salt mine requires the apparatus to be built very thoroughly. Salt powder and moisture are deposited during the work and therefore the whole apparatus must be tightly closed. These difficulties may be easier overcome if we use all-metal counters with earthed cathodes. Because of the very large fluctuations of voltage in the mine, the apparatus had to be supplied with a stabilizer stabilizing the voltage within wide limits. The magnetic stabilizer* which we used was very helpful in this matter. The special conditions of work also needed some additional arrangements to make work continuous and safe (such as an automatic switch for too low voltage, a delayed switch for switching on the high tension for register circuits, an electric clock starting by the above-mentioned delayed switch, etc.).

The measurements on the ratio of threefold to double coincidences were performed with an apparatus much improved in comparison with that of Barnóthy and Forró. The telescope consisted of three G-M counters 1, 2, and 3 (Fig. 1). The middle counter 2 was of larger dimensions than the two others. The telescope was protected against side showers by six anticoincidence counters. The double coincidences D of the counters 1 and 3, and the threefold coincidences T of the counters 1, 2, and 3 were registered simultaneously by two separate P.O. registers. In this way we have even for a not very great number of D coincidences a fairly small statistical error of the ratio T/D. This is very important here because of the very low intensity of cosmic radiation at the depths in which we have worked (the number of T coincidences at the lowest level is at the rate of about 1/hr.). In order to measure the double coincidences D, the resolving time of our apparatus had to be rather small. It was 2.6 μsec., which we obtained in such a way that the rectangular pulse coming from the counter amplifier was differentiated with a small time constant in the circuit of the grid of the Rossi

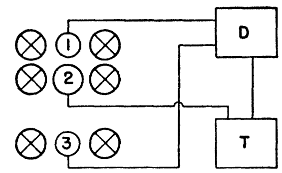

FIG. 1. Arrangement of counters.

valves.[7] The G-M counters we used were of the all-metal type filled with the usual argon-alcohol mixture.[7] The dimensions of the counters were:

counters 1 and 2	4.3×65 cm^2,
counter 3 and anticounters	5.2×70 cm^2.

The number of pulses per minute of these counters in the laboratory were about 650 for smaller and 900 for larger counters. The number of pulses per minute at the lowest level in the mine were about 70 and 100, respectively. After protecting the counters 1 and 2 by 5 cm Pb at the lowest level, the background rate dropped to 16/min. The low background rates of the counters were very convenient for our measurements.

THE MEASUREMENTS OF THE RATIO OF THREEFOLD TO DOUBLE, AND OF FOURFOLD TO THREEFOLD COINCIDENCES

In our preliminary measurements performed at two depths (660 m w.e. and 540 m w.e.) we found more double than threefold coincidences, proving in this way qualitatively even for those depths the existence of the effect found by Barnóthy and Forró at 1000 m w.e. We did not find, however, any difference between the number of threefold and fourfold coincidences. The results of the measurements are given in Tables I, II, and III. In all tables in the number of D coincidences there are subtracted the accidental coincidences.

INVESTIGATIONS OF THE PROPERTIES OF THE RADIATION CAUSING THE EXCESS OF DOUBLE OVER THREEFOLD COINCIDENCES

Let us write the number of double, threefold, and fourfold coincidences in the form:[8]

$$D=\lambda^2N+J,\quad T=\lambda^3N+J,\quad F=\lambda^4N+J,$$

where J is the intensity of the ionizing component of the radiation going through the telescope, for which we assume the efficiency of the G-M counter to be 1.0, N the intensity, and λ the efficiency of the G-M counter for the non-ionizing component. From our measurements of the ratio F/T, it follows that $\lambda^3N\ll J$; in other words, the number of threefold coincidences produced by non-ionizing component is negligible as compared with the number of threefold coincidences produced by the ionizing component. Then we may consider T as the intensity J of the ionizing component

* The authors are greatly indebted for the design and the construction of this to Mr. T. Czayka of the Cracow Mining Academy.

[7] M. Miesowicz and L. Jurkiewicz, Acta Phys. Polonica **IX**, 54 (1947).
[8] J. Clay and C. Levert, Physica **IX**, 158 (1942).

and write:

$$\frac{T}{D}=\frac{T}{\lambda^2N+T}=\frac{T}{A+T},$$

where A gives the number of double coincidences due to the non-ionizing component. Table IV gives a comparison of the values of A and T for two depths.

If A is considered as a measure of the intensity of the non-ionizing component of cosmic radiation, we should have its strong dependence on the depth and its high relative intensity. The ionizing component, however, shows that the intensity decreases in accordance with the measurements of other authors. For the absorption coefficient we get from our figures the value 2.1 which, taking into account our rather poor evaluation of the water equivalent, is quite consistent within the limits of error with the values given by other authors.

The other characteristics of the component A correspond in general to those found by Barnóthy and Forró for radiation recorded by double coincidences. For the investigation of the angular dependence of the component A, the measurements of threefold and double coincidences in a horizontal position of the telescope have so far been carried out. The results are given in Table V.

From the figures given in Table V we can see that for the horizontal position of the telescope the number of threefold coincidences is negligible and the number of double coincidences is, within the limits of error, of the same value as A. This is an evidence for the isotropic character of the component A.

Then we investigated the influence of lead put between the counters on the ratio of T/D. The figures are given in Table VI.

From these figures we can see that the component A is absorbed with an absorption coefficient of about 0.5 cm^{-1} Pb.

TABLE I. Vertical telescope at a depth of 660 m w.e.

	Number of coincidences and time	Average rate per hr.
Threefold coinc. T	321	1.34 ± 0.05
Double coinc. D	443	1.86 ± 0.06
Time (in hr.)	239.46	
Ratio of threefold to double coinc.	$T/D=(72.5\pm2.7)$ percent.	

TABLE II. Vertical telescope at a depth of 540 m w.e.

	Number of coincidences and time	Average rate per hr.
Threefold coinc. T	454	2.08 ± 0.07
Double coinc. D	660	3.01 ± 0.08
Time (in hr.)	218.6	
Ratio of threefold to double coinc.	$T/D=(69.0\pm2.2)$ percent	

EFFICIENCY OF THE COUNTERS FOR THE COMPONENT A

Barnóthy and Forró, who evaluated the ratio T/D at 1000 m w.e. and found the value 0.05, interpret this figure as the efficiency of the counters for the radiation giving the coincidences. We think that this would be correct only in the case when the telescope has not also registered a number of ionizing particles for which the efficiency of the G-M counters is equal to 1.0, and for which the numbers of double and threefold coincidences are the same. For the efficiency λ of the counter for radiation causing the excess of double coincidences, we have $\lambda<T/D$. On the other hand, in these circumstances we cannot at all evaluate the specific ionization as Barnóthy and Forró do. They give the value of 0.04 ion/cm N.T.P. air for this radiation. It is not known beforehand whether this radiation reacts on the counter producing ions in the gas of the counter or whether it gives secondaries in the walls of the counter and those initiate the discharge in it. In the first case, however, the efficiency of the counter would depend on the specific ionization of the gas contained in it, but in the second case it would depend on the probability of emitting secondaries in the walls entering the counter.

For rough evaluation of the efficiency of the G-M counters for the radiation A, we compared the number of counts of a single counter caused by the radiation which is absorbed by 5 cm Pb with the number of double coincidences A. We have at 660 m w.e., for a counter of a length of $l=65$ cm and a diameter of $a=4.3$ cm, the number of counts without screening 80/min., with a screen of 5 cm Pb from all sides 16/min., the number of counts due to the radiation absorbed in 5 cm Pb 64/min. If we assume that this radiation is isotropic for all the sphere, we have a dependence between the number N of counts and the flux j of the radiation and an efficiency λ of the counters for this radiation of the form:

$$N=\pi^2al[1+(a/2l)]\lambda j,$$

we get from it $\lambda j=0.022$/sterad. cm^2 min.

TABLE III. Vertical telescope at a depth of 540 m w.e.

	Number of coincidences and time	Average rate per hr.
Fourfold coinc. F	354	2.09 ± 0.07
Threefold coinc. T	356	2.10 ± 0.08
Time (in hr.)	169.3	
Ratio of fourfold to threefold coinc.	$F/T=0.995\pm0.04$	

TABLE IV. Comparison of the values of A and T for two depths.

Depth	Coincidences caused by non-ionizing comp. A	Coincidences caused by ionizing comp. T
540 m w.e.	0.93/hr.	2.08/hr.
660 m w.e.	0.52/hr.	1.34/hr.

TABLE V. The telescope in a horizontal position at 540 m w.e.

	Number of coincidences and time	Rate per hr.
Threefold coin. T	1	
Double coin. D	110	0.91
Time (in hr.)	129.6	

Let us now assume the probability of double coincidences due to this radiation without any discussion of the particulars of the mechanism of this process. Let us take λ' as the efficiency of the telescope for the double coincidences for this radiation, i.e., λ' is the probability that the particle or photon which discharges the first counter enters the second one and discharges this also. If the radiation is isotropic and comes from the solid angle determined by the telescope, we get by simple integration for the number of double coincidences A:

$$A=\lambda\lambda' ja^2(l/h)\arctan(l/h),$$

where $h=18$ cm is the distance between the counters in the double coincidence telescope. We get from this equation, $\lambda'=0.005$, a value 10 times smaller than that given by Barnóthy and Forró.

CONCLUSIONS

The results of this work therefore show the following properties of the radiation giving the excess of double over threefold coincidences: (1) It is scarcely ionizing. (2) It is isotropic. (3) It is absorbed by about 50 percent in 0.5 cm Pb. All these properties seem to prove that this radiation is of photon character, and the absorption coefficient and the efficiency of the counter for this radiation also suggest that we may have here some γ-radiation with energy ($\sim$1 Mev) of perhaps natural radioactive substances.

TABLE VI. The telescope in a vertical position at 540 m w.e.

Thickness of lead in mm	T/D	A	A/A(0 cm Pb)
0	0.690	0.93	1.00
5	0.795	0.49	0.53
10	0.906	0.19	0.20
15	0.930	0.13	0.14
50	0.989	0.02	0.02

It remains to explain the mechanism of the coincidences given by such radiation. Probably we may have to do here with an example of some interesting compound Compton effect. As a matter of fact it might be possible that a photon entering the first counter and discharging it might enter the second counter and give off another electron operating the counter.

It is possible to see from our evaluation of the efficiency of the counter for that radiation, assuming that the discharge in the counter is started by photons, that we get quite a reasonable figure for the efficiency for double coincidences. Of course, in this case, $\lambda'<\lambda$ because the loss of energy of photons in the first counter causes a drop in the efficiency, and the photons are dispersed causing in this way also an additional inefficiency.

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