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A NEW EXPERIMENT BEARING ON COSMIC-RAY PHENOMENA

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Abstract

This new experiment consists in combining a Wilson cloud expansion apparatus with Geiger-Müller electron-counters in a manner which allows the simultaneous study of individual cosmic-ray particles by the two methods. Its purpose was to see whether the coincidence effect in electron-counters is actually caused by the passage of an ionizing particle through them as has been generally assumed. This was considered desirable because it was felt that the several conflicting cosmic-ray experiments could perhaps be more satisfactorily explained by assuming the coincidences to be produced by photons. In this work a series of expansion photographs was taken under experimental conditions which allowed a definite correlation of an ion-track appearing in the expansion chamber with a discharge of a Geiger-Müller counter. It was found that the discharges of a counter due to cosmic radiation are accompanied by ion-tracks resembling those due to fast β-rays from radioactive sources. This result means that, in accord with previous beliefs, the coincidence effects are caused by ionizing particles. The best assumption we can make at present appears to be that these are high-energy electrons. The possibility that these effects are due to photons appears to be excluded, so that the reconciliation of the conflicting experimental data in this field will have to follow other lines.

Introduction

Since the discovery by Bothe and Kolhörster[1] that the cosmic radiation produces simultaneous discharges when passing through two Geiger-Müller[2] electron-counters placed one above the other, it has been generally assumed that this "coincidence effect" is caused by the passage of an ionizing material particle (presumably a high-energy electron) through the counters. This view appeared entirely reasonable, for the only other simple hypothesis, that the effect is caused by the passage of a photon through the counters, was shown by these investigators to be unable to account for their result unless some new phenomenon was concerned. On the other hand it is interesting to note that the recent failure of attempts by Rossi[3] and by Mott-Smith[4] to produce a magnetic deviation of these corpuscles could perhaps be more satis-

[1] W. Bothe and W. Kolhörster, Zeits. f. Physik **56**, 751 (1929). See also the more recent work of B. Rossi, Cim. (N. S.) **8**, 49, (1931) No. 2.
[2] H. Geiger and W. Müller, Phys. Zeits. **29**, 839 (1928).
[3] B. Rossi, Rend, Acc. dei Lincei **2**, 478 (1930).
[4] L. M. Mott-Smith, Phys. Rev. **37**, 1001 (1931).

factorily explained on the basis of photons. In these experiments, which were made with apparatus involving coincidences in electron-counters, no detectable magnetic deflection of these supposed electrons was observed, though in the work by Mott-Smith, electrons with an energy of as large a value as 2×10^9 e-volts would have given a readily measurable effect. As has been pointed out by the above investigator, there are at present certain serious difficulties in interpreting these experiments to mean that an electronic radiation of such enormous energy exists. If, however, the coincidence effects were produced by the passage of a photon through the apparatus, the lack of deflection is at once explained. In addition, if this were the case it would be clear at once why the Bothe and Kolhörster[1] absorption experiments with counters gave the same cosmic-ray absorption coefficient as that obtained by the electroscope work. It must be added, however, that essential additions to the known properties of photons would have to be postulated to allow this interpretation. In view of our relatively uncertain experimental knowledge with regard to the nature of γ-type radiation having the penetrating power of the cosmic-rays it is believed that such a procedure might be allowable.

A further difficulty with ascribing the coincidence effects to photons comes from the work of Skobelzyn.[5] From his work with the Wilson expansion-chamber it is known that the earth's surface is being bombarded by a radiation composed of high-energy electrons whose energy, intensity, and distribution about the vertical indicate that it is in some way connected with the cosmic radiation. It has been assumed that this radiation is the same as that responsible for the coincidence effects. However, this assumption rests on rather indirect and approximate considerations which might be questioned in view of the result of the deflection experiments as well as the other difficulties in this field.

Consideration of the foregoing type led us to look for a direct experimental method which could decide between these two possibilities.

Experimental

General considerations.

It was decided that a suitable method consisted in combining a Wilson cloud-chamber with Geiger-Müller counters in a manner that permitted the simultaneous study of individual cosmic-ray particles (or photons) by the two methods. For example, if a cloud-chamber is interposed between two counters so that every particle which operates the counters by passing through them must also pass through the chamber, ion-tracks appearing in the chamber can be correlated with the discharges of the counters. This correlation can be made quite definite. A track in the chamber will only be formed during a time-interval of about 0.05 sec. just after the expansion is completed, so that only particles which operate the counters during this interval can be expected to produce a track. Since with the counting-rates attainable the chance of obtaining more than one discharge during the "sensitive" interval is negligibly small, the appearance of tracks at the expansions

[5] D. Skobelzyn, Zeits. f. Physik **54**, 686 (1929).

for which the counters discharged during this interval is a definite indication that the discharge and the track were produced by the same particle.

If a correlation between such tracks and the counter discharges were found, it would be good evidence that the coincidence effects in electron-counters are caused by ionizing particles. A failure to find tracks associated with the discharges would speak in favor of photons if these are assumed to have the properties of ordinary γ-rays, since such photons are known to produce no observable track in traversing a cloud-chamber. The question arises, however, whether it is possible to distinguish in this manner between ionizing particles on one hand, and on the other, photons for which the minimum of new properties are postulated which suffice to account for the coincidence effects. In order that a cosmic-ray photon may cause the observed coincidence phenomena it must be nearly certain to produce at least one ion in each counter through which it passes. On the Compton theory the average energy given to the recoil electrons is in the case of cosmic radiation so great that the "mean free path" of the photon is too large to give even a fair probability of production of an ion in each counter. What is needed here is an additional process, by which such a photon can produce a series of low-energy ions along its path in a manner analagous to the ion-track formation by β-particles or other ionizing particles. To explain the coincidences, these "photon-tracks" would need to have only one or less ion-pairs per cm path in air under normal conditions. Hence such an interpretation might be allowable without contradicting existing experimental facts, particularly since such a process need be postulated only for high-energy photons. However, it appears fairly certain that these hypothetical photon-tracks cannot be assumed to have anything approaching the density of ionization of those due to even the fastest β-particles. This is on account of the unallowably great loss of energy which the photon would undergo in passing through absorbing media. Accordingly, the presence or absence of ion-tracks associated with the counter-discharges can be expected to give the desired information.

Apparatus and preliminary tests.

The apparatus which was actually set up differs from the arrangement described above (for purposes of illustration) on account of certain experimental difficulties. Instead of placing two counters one above and one beneath the expansion-chamber, a single counter was used, located directly above the chamber. This simplification was found necessary because it turns out that with any feasible arrangement involving two counters the passage of cosmic-ray corpuscles through the pair is altogether too infrequent to render the experiment possible. However, our single-counter arrangement is capable of giving just as significant results. In the first place, as will appear below, we can expect that a sufficiently large fraction of the discharges of the single counter are due to cosmic-ray corpuscles which pass through the expansion chamber. Secondly, it is known from the work of Bothe and Kolhörster and others that the ratio of the cosmic-ray counting-rate for the single impulses of one counter to that for paired coincidences in two such counters is about what is expected from the geometry of the arrangement, assuming that all the particles which give the single impulses would give coincidences if a second counter were in position to receive them. Accordingly, there can be little doubt that in our experiments with the single counter we are studying the corpuscles which are responsible for the coincidence effects.

The relative positions of the expansion chamber E and the Geiger-Müller counter T_1, T_2, as well as of the cameras C for taking the expansion-photographs are indicated by Fig. 1 which represents two side-elevations of the apparatus. (The cameras have been schematically represented in this figure by simply drawing the plates and lenses.) It will be noted that two counters are shown (at T_1 and T_2). These, however, are connected to the amplifier (see Fig. 2) in such a manner that they operate exactly like a single counter of larger cross-sectional area, and can be so considered in what follows.

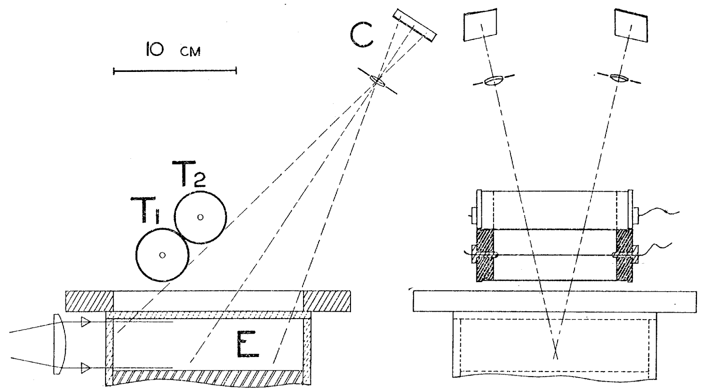

Fig. 1.

The expansion-chamber is the same as that previously described by Locher;[6] its details need not be entered into here. The operation of the chamber was tested by observing the tracks due to recoil β-particles produced by the γ-radiation from a small quantity of radium, filtered through 3 mm of lead. This test was repeated at frequent intervals during the taking of the expansion photographs to insure that the expansion-chamber and associated apparatus remained in proper working condition. The source of illumination was a new type of mercury "flash" arc, developed by the junior author, a full account of which will be published in a separate article.

The Geiger-Müller counters were of a simple construction similar to that used in the first work of Bothe and Kolhörster.[1] A section through one of them is shown in Fig. 1. The tubes were brass of 1.0 mm wall thickness with hard rubber end-pieces carrying little brass holders to which the central wire was attached. The wire was tungsten about 0.076 mm in diameter and had no special treatment of the surface except careful removal of dust just before introduction into the counter. The counter contained air at about 7 cm of mercury pressure.

Tests of the counting-rates of the two counters gave a value of about 55 impulses per minute for each, a rate which is about normal for tubes of these

[6] G. L. Locher, J.O.S.A. & R.S.I. 19, 58 (1929).

dimensions and under our conditions of sea level and about one meter water-equivalent shielding by the parts of the building above the apparatus. Sensitivity tests with γ-radiation from a small quantity of radium were also satisfactory, one milligram of radium at 4.6 meters increasing the count to about 150 discharges per minute.

It is also necessary to know what fraction of the counter-discharges are due to cosmic radiation. To find what fraction of the count is due to radioactive γ-radiation from the surroundings, the counting-rate of one of the counters was determined while it was shielded on all sides by a lead shield approximately 2.5 cm thick. This shield reduced the count from 58.8 to 34.5 per minute. The effect of this shield on the intensity of the local γ-radiation was calculated by taking the absorption coefficient of this radiation to be 0.49 per cm of lead. Its effect on the cosmic radiation could be neglected. It is also necessary to allow for the "zero count" due to the radioactivity of the counter itself and other internal causes. For this the value 6 impulses per minute based on the determination by Bothe and Kolhörster was taken. This approximation was made on account of the difficulty of making tests with the

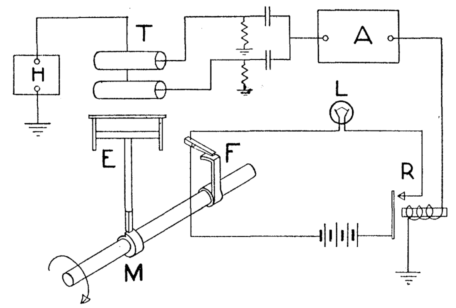

Fig. 2.

counter in a completely radiation-free region. In this manner it was determined that 0.30 ± 0.05 of the discharges of the counters were due to cosmic radiation.

Fig. 2 shows very schematically the auxiliary apparatus of interest. The source of potential for the counters, *H*, consisted of a thermionic rectifier and condenser furnishing the required potential of about 1500 volts. The amplifier *A* was of the usual three-stage vacuum-tube variety. It operated the relay *R* which had a fairly light armature and was adjusted to operate with as short a time lag as possible. Oscillographic tests showed that the relay remains closed for somewhat less than 0.01 sec. at each counter-impulse. This relay closed the circuit as indicated. The purpose of this circuit and associated apparatus was to signal the occurrance of a counter-discharge during the time interval that the expansion-chamber is in the sensitive condition, an event which may be termed a coincidence. The operation of this "coincidence signal" will be clear from an examination of the figure. The expansion is made by setting the cam *M* into rotation as indicated by the arrow. Carried on the same shaft with the cam is a finger *F* which closes a pair of contacts just after the expansion is completed and keeps them closed for a predetermined interval. This finger was adjusted so that it held the contacts closed only during the sensitive interval. (The adjustment was made by observing tracks due to photoelectrons from a short flash of x-rays which could be made to occur at varying time intervals after the expansion. Tests with an oscillograph showed that these contacts remained closed for an interval of 0.06 sec.) Thus the signal lamp L will only light when a coincidence occurs. Observation of the signal lamp during the taking of the expansion photographs allowed the coincidence photographs (on which a track might be expected) to be distinguished from those for which there was no discharge of the counter. For convenience the coincidence photographs are designated as C-photographs while the rest are called N-photographs.

Procedure and results.

The principal experiment consisted in setting the counters in operation and taking a series of expansion photographs. These were separated into the C and N groups with the aid of the coincidence signal by marking on the films (just after taking the photograph) those exposures for which a coincidence occurred.

In agreement with the work of Skobelzyn, an examination of these photographs revealed a considerable number of very thin straight tracks resembling those due to the fastest of ordinary β-rays, but somewhat thinner. An inspection of magnified sections of several of these tracks indicated that the number of ions per cm path was about half of the value observed for an average recoil β-particle from radium C γ-rays filtered through 3 mm of lead. We were not equipped to show, in the manner done by Skobelzyn,[5] that a majority of these tracks were not appreciably deflected in a magnetic field of such strength that it could strongly deflect β-rays from radioactive sources. However, on account of the positive result of the present experiment it cannot be doubted that a considerable fraction of these tracks were due to cosmic corpuscles. Further evidence in this direction came from a study of the distribution about the vertical for the 134 thin straight tracks which were found on our photographs. It was found that this distribution was in approximate agreement with the distribution of cosmic-ray particles observed by Tuwim.[7]

It was necessary to know the position and direction of each of these tracks not only for obtaining the distribution just mentioned but also on account of the following circumstance. In attempting to establish a correlation between a certain track appearing on a C-photograph and the discharge of the counter, we must make use of only the tracks whose prolongation passes through the counter. Tracks which do not fulfill this condition are due to cosmic corpuscles which entered the chamber without passing through the counter, to radioactive β-particles originating within the chamber, or other spurious causes. These tracks, of course, must be excluded from consideration. For these reasons a stereoscopic analysis was made of the 134 tracks. This was done by a visual reconstruction method similar to that used by Curtiss[8]

[7] Leo Tuwim, Berliner Ber. No. 4/5, p. 91, (1931).

[8] F. L. Curtiss, Bureau of Stds. Jour. of Res. **4**, 663 (1930).

which allowed fair accuracy with considerably less labor than an analytical method.

With the present single-counter arrangement, it is evident that not all the C-photographs can be expected to show a track of the significant kind. Besides, a certain number of such tracks must be expected on the N-photographs due to spurious causes. Hence what must be looked for is whether there is a significantly larger probability of finding a track (of the required type) on a C-photograph than on an N-photograph. Accordingly, the probability of finding such a track on a photograph was computed for each of the two classes of photographs from the experimental data.

TABLE I. *Numerical results.*

Series	Number of		Number of significant tracks observed on		Probability of occurrence of a track on	
	C-Phot.	N-Phot.	C-Phot.	N-Phot.	C-Phot.	N-Phot.
1	—	659	—	15	—	0.023 ± 0.004
2	68	—	6	—	0.088 ± 0.024	—
3	69	448	6	11	0.087 ± 0.024	0.025 ± 0.005
Averages and totals	137	1107	12	26	0.088 ± 0.017	0.024 ± 0.003

The numercial results are presented in Table I. It will be noted that th data for the C-photographs are missing for the first series while those for the N-photographs are for the second. This apparent inconsistency is due to the fact that during the taking of the first series only the upper of the two counters (T_2) was employed. After examination of both the N and the C-photographs in this series, it was found that the chance of a cosmic-ray particle passing through this counter and the chamber was too small to render the experiment feasible. In order to increase this quantity to a reasonable value, the second counter (T_1) was added before taking the remainder of the photographs. Since the examination and stereo-analysis of the numerous N-photographs involved considerable labor, this class of exposures for the second series was not examined but those from the first series are to be used for comparison with the C-photographs of the second. This procedure is legitimate since no changes were made in the manner of taking the photographs or in the expansion chamber, and the taking of the N-photographs is quite independent of the presence of the counters.

Comparing the probability of finding a significant track on an N-photograph to that on a C-photograph, it is seen that a considerably higher value is found for the latter. The probable error has been computed by taking the statistical error of the number of observed tracks to be 0.67 $N^{1/2}$, where N is this number. The difference between the two averages (0.088 and 0.024) is 0.064, while the probable error of the difference is 0.017. Accordingly it is very unlikely that this differences is accidental. The fact that the values for the last series check with the previous ones even better than could be hoped is also evidence in this direction.

This result indicates a definite correlation between the discharges of the counter and the appearance of a track in the chamber. Or, in other words, at least one of the agents which cause the discharges of the counter produces tracks in the expansion-chamber. It must now be shown that this agent is the cosmic-radiation. One possibility is that our result is due to β-particles from radioactive sources. One simple way to account for it is to assume that a β-particle which originates inside the counter reaches the interior of the chamber, or vice versa. This particle must do so without undergoing much deviation and while still endowed with considerable energy. In order to pass from counter to chamber the β-particle has to penetrate through an amount of material corresponding to about 4 meters of air. It is evident that ordinary β-particles or recoil electrons due to γ-radiation from radioactive sources do not have sufficient penetrating power to make such an event possible. Another way by which the present result might be explained is to assume that a primary γ-ray or cosmic-ray photon produces a recoil electron in the counter and that the scattered photon in turn produces a second recoil electron in the chamber, whose track is observed. This process has been considered by Bothe and Kolhörster[1] as a possible explanation of coincidences between two counters. Their analysis also applies to our case. They found that the chance of occurrence of this compound process is so small that it can only account for a negligibly small part of the observed coincidences. Accordingly we can conclude that our result cannot be explained in this way. It seems that the only possibility remaining is the one previously indicated, namely that the track is produced by a cosmic-ray particle which travels through both the counter and the chamber. Further evidence for the correctness of this view comes from the following calculation of the probability of finding a track on a *C*-photograph which may be expected on this assumption.

Calculation of C-probability.

In making this calculation two numerical factors are needed, the first due to the fact that not all the counter-discharges are due to cosmic radiation, the second on account of the circumstance that only a part of the cosmic-ray corpuscles striking the counters will pass through the expansion-chamber. The first factor, the fraction of the counter impulses due to cosmic radiation, was found in the manner already described to be 0.30 ± 0.05. The second quantity is the quotient of the number of particles passing through both the counter and the chamber by the total number striking the counter. It was approximately calculated by a simple geometrical consideration and under the assumption (justified by the work of Tuwim[7] and others) that the cosmic-radiation can be considered as all arriving within an angle of 70° from the vertical. The absorption of the radiation in passing from the counter to the interior of the chamber could, of course, be neglected. In this manner the value 0.066 ± 0.015 was found for the calculated probability of occurrence of a track on a *C*-photograph. In comparing this value with the experimental value 0.088 it must be noted that a portion of the tracks on the *C*-photographs are due to spurious causes. A rough assumption which may be made to allow for this fact is to take the probability of finding a spurious track on a *C*-

photograph to be the probability of occurrence of a track on an N-exposure. Accordingly the experimental value becomes 0.088–0.024 or 0.064 which is in good agreement with the calculated quantity. The closeness of this agreement is, of course, accidental on account of the uncertainties in both values but the comparison shows that our experimental value is about what can be expected.

Discussion

It seems reasonable to conclude from the foregoing that the cosmic-ray corpuscles which cause the coincidence effects in Geiger-Müller counters produce ion-tracks resembling β-ray tracks. It does not appear possible that such tracks could be produced by photons, so that, in agreement with previous beliefs, it appears that the coincidence effects are due to material particles. Accordingly the present result indicates that attempts to explain the coincidences by the direct action of photons must be abandoned.

Another interpretation of this experiment which requires consideration is to suppose that the observed tracks were due to a particle of secondary origin produced by a primary corpuscle which causes the coincidences but whose passage through the cloud chamber was not detected.* As had been indicated above, these tracks could not be due to a secondary recoil electron produced by a photon as the primary corpuscle. However, the possibility remains that they were produced by a primary material particle, such as a high-energy electron, whose passage through the chamber was not detected, perhaps because the track of ions which it leaves is too thin to be observable. Although further work on this subject may show this to be the correct interpretation of the present experiment, it appears to us that the following circumstances speak against this view. The foregoing calculation of the chance of finding a track on a C-photograph shows that practically all the cosmic particles which pass through both the counter and the chamber produce an ion-track. This means that to render this hypothesis tenable, every primary particle passing through the chamber must produce a secondary one therein. Moreover, on account of the requirement that the observed tracks must be directed to pass through the counters, these secondary particles must be set off roughly in the direction of the primary one. If the primary particle were to produce relatively high velocity secondary ones as frequently as is necessary to account for the present result, its penetrating power would be less than is observed unless it is assumed to have an excessively high initial energy. Furthermore, it is felt that the second requirement cannot be readily met, though in absence of any exact knowledge of such a process in this region of energy little more can be said. Accordingly, it seems that the best assumption we can at present make is that both the discharge of the counter and the associated track are directly caused by a single cosmic-ray particle as originally supposed.

With regard to the character of these material particles very little can be said with assurance. At first sight it would seem that the thin tracks we have

* While this article was in preparation, a paper by Jeans appeared in which he states that the result of the magnetic deflection experiments must be taken to mean that the coincidence effects are due to photons. We believe that our present result renders this view untenable. J. H. Jeans, Nature **128**, 103 (1931).

observed could be produced by nothing other than high-energy electrons. Furthermore, if, as seems fairly certain, these tracks are of the same character as those observed by Skobelzyn, from this work comes additional strong evidence in this direction. However, if such were the case, it would have to be assumed, on account of the electron-counter absorption experiments,[1] that these electrons constitute the major part of the primary cosmic radiation. Then the magnetic deviation experiments as well as the observed lack of dependence of the intensity of the cosmic radiation on the magnetic latitude[9] would require that the energy of these electrons be the enormous value of the order of 10^{11} e-volts. This at present seems improbable not only on the grounds of explaining how the electron acquires this enormous energy but also because on present theoretical ideas the penetrating power of such an electronic radiation would be considerably greater than is observed for the cosmic-radiation. The same sort of difficulties would apply if the coincidences were due to protons and perhaps if they were due to heavier particles, through the observed small density of ionization seems to speak against the possibility that they are even of the mass of a proton.[10]

Another possibility which should be mentioned is that we may be dealing with a totally new type of particle. Recently the existence of such a particle, the "neutron," has been tentatively postulated by Langer and Rosen[11] and also by Pauli.[12] As Pauli has pointed out, if the coincidences were produced by such a particle, the absence of magnetic effects is at once clear, since, as its name indicates, it carries no charge. It is evident, however, that this particle would be required to have properties similar to those of an electron as far as ionizing ability is concerned. Though, according to Pauli, this may turn out to be the case, the whole matter is as yet too uncertain to allow even a tentative explanation on this basis at the present time. If it turns out that the neutron possibility must be excluded, it seems on the whole that the best assumption we can make is that these particles are electrons.

It has been the object of this paper to present what we believe to be strong experimental evidence that the coincidence effects are directly due to ionizing material particles, to the definite exclusion of photons. The authors feel that the question of the nature of these particles and the related problem of the general significance of this result for cosmic-ray theory must be left open since they believe that no definite conclusion can be reached at present.[13,14]

[9] R. A. Millikan, Phys. Rev. **36,** 1595 (1930); R. A. Millikan and G. H. Cameron, Phys. Rev. **37,** 235 (1931).

[10] Geiger has recently obtained experimental evidence in favor of protons. See, Discussion on Ultra-Penetrating Rays, Proc. Roy. Soc. **A128,** 331 (1931).

[11] R. M. Langer and N. Rosen, Phys. Rev. **37,** 1579 (1931).

[12] W. Pauli. Presented in a speech at "Symposium on Nuclear Structure" at the summer meeting of the A.A.A.S., June 16, 1931. As yet unpublished.

[13] The present position of the investigation in this field is well presented by "L. H. G." in a summary in Nature **127,** 859 (1931).

[14] A part of the expenses of this experimental work were met by a grant to the junior author from the National Research Council.