A Coincidence Test of the Corpuscular Hypothesis of Cosmic Rays

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Three Geiger-Müller counters were arranged vertically so that double coincidences were recorded by the counters 1 and 2 and triple coincidences by counters 1, 2 and 3 simultaneously. The third counter was permanently shielded by a lead cylinder of 2.5 cm thickness which is sufficient to absorb all the secondaries produced in the absorber. Counts were made under three conditions:

	Double(hr.$^{-1}$)	Triple(hr.$^{-1}$)
(A) Without lead absorber	202.44±1.84	42.43±0.83
(B) With 20 cm of lead between counters 1 and 2	124.48±1.43	30.50±0.50
(C) With 20 cm of lead above counter 1	142.17±1.08	32.55±0.52

The reduction in the number of counts due to the lead was thus slightly greater in position B than in position C. That this difference can be ascribed to secondaries is shown by the fact that B/C is less for the double coincidences than for the triple ones. The data can be interpreted by assuming that the coincidences are due chiefly to penetrating ionizing particles, some of which are stopped by the lead (for which B should equal C), with the addition of a few coincidences in case C due to secondaries produced in the lead by a penetrating ray associated with a penetrating particle traversing the shielded tube 3. It does not appear possible to account for these coincidences in terms of corpuscles excited by photons unless the photons either are absorbed in the atmosphere before reaching the apparatus, or are accompanied throughout their path by ionizing particles, which would practically mean treating the photons as ionizing particles. That is, the coincidences seem to be due to penetrating ionizing particles and not to secondary particles produced by photons which traverse the lead. This view is further supported by the close agreement of the absorption coefficients computed from this experiment ($\mu = 2.2\times10^{-3}$ cm^{-1}) with those determined from ionization chamber measurements of the cosmic rays ($\mu = 1.90\times10^{-3}$ cm^{-1}).

It has been pointed out by Compton,[1] Auger[2] and others[3] that the hypothesis of charged corpuscles is adequate to account for the effect of the earth's magnetic field on the intensity and angular distribution of cosmic rays, for their absorption in the atmosphere and in deep water, and for the various coincidence experiments performed with Geiger-Müller counters. A few investigators, including Millikan[4] and Regener,[5] impressed by the close agreement between the absorption coefficient of the strong softer component of cosmic rays and that calculated for photons resulting from various types of nuclear transformations, have preferred the photon hypothesis.

In 1929 Bothe and Kolhörster[6] developed a coincidence method for counting the penetrating particles. From the fact that the absorption in gold of the particles producing the coincidence was nearly the same as that of the cosmic rays as measured with ionization chambers, they identified these corpuscular rays with the cosmic radiation itself. When Rossi[3, 7] repeated Bothe and Kolhörster's experiments he found that secondaries are produced in lead by cosmic rays, which are also able to produce coincidences. Using three counters, Rossi confirmed Bothe and Kolhörster's results by showing that up to a thickness of 101 cm of lead the absorption of the coincidences follows closely that characteristic of cosmic rays as found by depth-ionization measurements. Yet in this work also the results were somewhat confused by the presence of secondaries. Rossi showed that the mean penetrating power of these secondary particles was about one cm of lead, and argued that since only those secondary particles produced in the lowest layer of the absorber could get out, the coincidences which they produce should be a constant fraction of the total number. More recent studies by Rossi,[7] Swann and Montgomery,[8] Johnson and Street,[9] and others have

[1] A. H. Compton, Nature **131**, 713 (1933); Science **77**, 480 (1933); The Science of Radiology, 398 (1933); Phys. Rev. **45**, 441 (1934).

[2] P. Auger, J. de physique et le radium **5**, 1 (1934).

[3] B. Rossi, Zeits. f. Physik **68**, 64 (1931); Rend. Lincei **15**, 734 (1932); La Ricera Scientifica **3**, No. 7 (1932); A. Corlin, Annals Univ. Lund. No. 4 (1934); J. Clay, Amsterdam Proc. **35**, 1282; **36**, 62 (1933); T. H. Johnson, Phys. Rev. **41**, 545 (1932).

[4] R. A. Millikan, Phys. Rev. **43**, 661 (1933), *et al.*

[5] E. Regener, Phys. Zeits. **34**, 880 (1933), *et al.*

[6] W. Bothe and W. Kolhörster, Zeits. f. Physik **56**, 751 (1929).

[7] B. Rossi, Zeits. f. Physik **82**, 151 (1933); Nature **132**, 173 (1933).

[8] W. F. G. Swann and C. C. Montgomery, Phys. Rev. **44**, 52 (1933).

[9] T. H. Johnson and J. C. Street, Phys. Rev. **40**, 638 (1931); **42**, 142 (1932).

shown also that frequent coincidences result from showers of ionizing particles which originate in the roof of the building and sometimes in the atmosphere itself. The number of such coincidences in Rossi's absorption experiments was presumably nearly independent of the thickness of the lead.

The present paper describes a coincidence experiment performed under such conditions that coincidences due to showers of ionizing particles and of secondaries from the lead absorbers can be distinguished from those due to primary ionizing particles passing directly through the counters. A measurement of the absorption of these primary particles in the lead is also obtained.

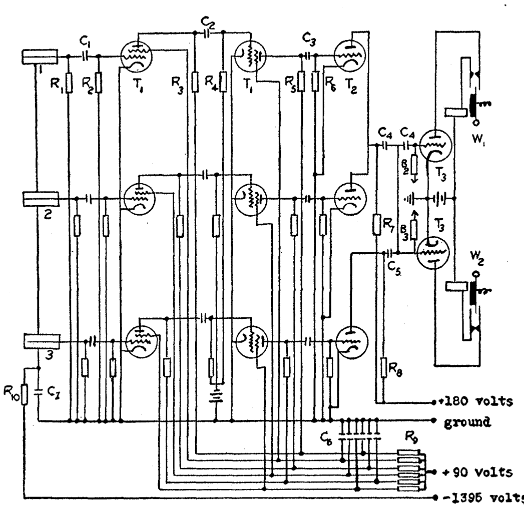
In one of Rossi's early experiments, using a double coincidence counter, he placed the absorbing lead alternately above and between the counting tubes. If the coincidences were due entirely to penetrating particles directly traversing both counters, the effect of the lead in stopping these particles and reducing the coincidence rate should be the same in both positions. If, however, photons should produce secondaries in the lead capable of passing through the counters, coincidences might be produced with the lead block above the counters, but not if placed between, since the photon would not itself ionize the gas in the first counter. The experiment showed a lower counting rate with the lead between the two tubes than when placed above them. This could be explained as due to a mixture of primary photons and ionizing particles, or as due to primary ionizing particles which may produce secondaries in the lead.

The present experiment is similar to that of Rossi except that a third counter, shielded with 2.5 cm lead, is placed below the other two. The results obtained with this arrangement are such as to show that if photons produce any ionizing secondaries in the lead blocks, they have a range of less than 2.5 cm in lead, and are thus to be distinguished from the penetrating particles responsible for the triple coincidences. The absorption of the penetrating particles by the lead is in close agreement with the value found by Rossi, when his value is corrected for the effect of spurious coincidences, and supports the view taken by previous experimenters that these penetrating ionizing particles may be identified with the primary cosmic rays.

Apparatus and Procedure

Three Geiger-Müller counters were made in the laboratory according to the technique of Mott-Smith.[10] The sheet copper tube is 4 cm in diameter and 25 cm long. The central wire is of tungsten, 0.025 mm in diameter. The tubes were cleaned, evacuated, baked out and filled to 4.5 cm pressure with cleaned air and a trace of iodine vapor. All tubes were tested for uniformity on the counter circuits before sealing off.

The amplifying circuit shown in Fig. 1, was based on that described by T. H. Johnson.[11] It was, however, so arranged that the circuits 1 and 2 form double, and these together with circuit 3 form triple coincidences. Coincidences are recorded by an electromagnetic device which



1, 2, 3, G–M counters
R_1, 10^{10} ohms
R_2, 10^7 ohms
R_3, 5×10^4 ohms
R_4, 10^6 ohms
R_5, 2×10^4 ohms
R_6, 10^5 ohms
R_7, 5×10^4 ohms
R_8, 2.5×10^4 ohms
R_9, 2×10^4 ohms
R_{10}, 10^6 ohms
C_1, 10^{-6} mf
C_2, 2×10^{-2} mf
C_3, 2.5×10^{-4} mf
C_4, 6×10^{-3} mf
C_5, 2×10^{-3} mf
C_6, 2 mf
T_1, tube 24A
T_2, tube 27A
T_3, thyratron No, 1 (256A)
T_3, thyratron No. 2 (256A)
W_1, watch recorder for doubles
W_2, watch recorder for triples
B_2, C-bias (-45 v) on thyratron 1
B_3, C-bias (-55 v) on thyratron 2

Fig. 1.

[10] L. M. Mott-Smith, Phys. Rev. **39**, 403 (1932).
[11] T. H. Johnson and J. C. Street, J. Frank. Inst. **215**, 239 (1933).

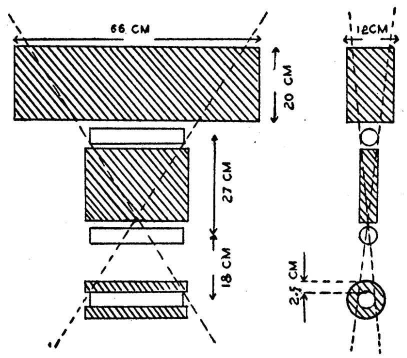


FIG. 2.

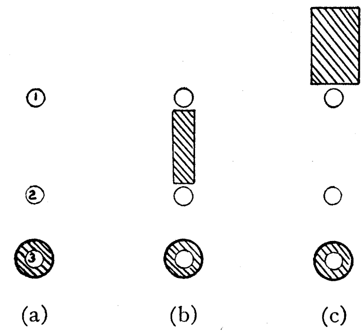


FIG. 3.

operates the escapement of a watch and also serves to break the plate circuit of the thyratron. After proper voltage adjustment, the apparatus was given repeated tests by the application of a negative potential to the grid of the first stage of each circuit separately and jointly. It was found that thyratron No. 1 went off only when the negative potential was applied to the grid of the first stage of circuits 1 and 2 or all the three circuits, and thyratron No. 2 went off only when the negative potential was applied to the grid of the first stage of all three circuits. In order to insure the necessary constant voltages in spite of the considerable current demand, a combination of accumulator batteries and *B* eliminators was used. It was thus possible to prevent the counting rate from varying appreciably throughout the several months required for the experiment.

Referring to Fig. 2, the three counters were arranged vertically so that double coincidences were recorded by counters 1 and 2 and triple ones simultaneously by counters 1, 2 and 3. The distance from center to center was 18 cm between counters 1 and 2, and 27 cm between counters 1 and 3. The lead cylinder permanently surrounding the third counter was of sufficient thickness (2.5 cm) to absorb all the secondaries produced in the lead absorber placed above.* The thickness of the absorbing block for different experimental conditions was always the same, 20 cm; but the area of the horizontal cross section was determined by the geometrical configuration in relation to the separation of the counting tubes. This is shown in Figs. 2(a) and 2(b).

Counts were made under three conditions:

(A) With no absorber . . . . (Fig. 3(a))
(B) With absorber between counters 1 and 2 . . . . (Fig. 3(b))
(C) With absorber above counter 1. (Fig. 3(c))

From the coincidences so recorded the false coincidences must be subtracted in order to obtain the abundance of the systematic coincidences. Theoretically, the number of the accidental double coincidences may be calculated[11] in terms of the relaxation time and the individual counting rate. Practically it was preferred to count the accidentals directly by placing all the counters in a horizontal plane.

Preliminary readings taken in the basement of Eckhart Hall are tabulated in Table I. Under

TABLE I. *Preliminary counts in basement of Eckhart Hall.*

Case	Coincidences Observed		Accidentals		Systematic	
	Double (hr.$^{-1}$)	Triple (hr.$^{-1}$)	Double (hr.$^{-1}$)	Triple (hr.$^{-1}$)	Double (hr.$^{-1}$)	Triple (hr.$^{-1}$)
A	142.33±3.4	28.13±1.5	29.9	0.9	112.43±3.4	27.23±1.5
B	121.70±3.1	23.98±1.4	29.9	0.9	91.80±3.1	23.08±1.4
C	129.35±3.2	24.00±1.4	29.9	0.9	99.45±3.2	23.10±1.4

condition *B* one should expect a decrease both in double and triple coincidences due to the absorption of the primary corpuscles. Under condition *C* the amount of primary rays absorbed should be the same as under condition *B*, but the secondary rays generated in the lowest part of the absorber should increase the double coincidences, without any effect, however, on

* This point was tested by auxiliary experiments in which a shield of 8.0 cm was used. The results were unchanged by this heavier shield.

TABLE II. *Summary of counts taken on roof of Ryerson Laboratory.*

Case	Hours	Total double	Total triple	Double ($hr.^{-1}$)	Triple ($hr.^{-1}$)
A	60	12,146.56	2,546.56	202.44 ± 1.84	42.43 ± 0.83
B	$120\frac{1}{2}$	15,002.09	3,676.40	124.48 ± 1.45	30.50 ± 0.50
C	$121\frac{5}{12}$	17,261.84	3,953.30	142.17 ± 1.08	32.55 ± 0.52

the triple because of the shield on counter 3. It is to be noted that the last two columns in Table I give exactly the expected result.

In order to reduce the effect of secondaries from the walls of the building the apparatus was finally installed within a thin wooden shelter on the roof of Ryerson Laboratory. The double and triple coincidences were continuously registered as before under each of the three conditions A, B and C, the results being summarized in Table II. The registration duration for the individual readings was 20 hours. During this time readings of the two watch recorders were taken at different intervals and the voltages on different parts of the apparatus were frequently checked. It will be seen that the double coincidences in case C are more frequent than in case B, in accord with Rossi's finding. The ratio of the counting rate B/C for triple coincidences, 0.94 ± 0.02, is, however, nearer to unity than the corresponding ratio for double coincidences, 0.88 ± 0.01.

INTERPRETATION

This result was to have been expected if most of the coincidences are due to ionizing particles passing directly through all three counters, for they should produce secondaries in case C which though capable of penetrating counters 1 and 2 to give double coincidences, would not enter the shielded counter 3 to give a triple coincidence. The small remaining difference between the triple coincidences in cases B and C may be explained thus: A primary particle on traversing the large lead shield in case C ejects from it secondaries which enter counters 1 and 2, while the penetrating primary particle passes on through counter 3. An adequate corpuscular interpretation of the result is thus readily found.

Let us now investigate the possibility of accounting for these results on the view that the coincidences result from secondary beta-particles produced by photons. For simplicity, we shall assume that all the secondary beta-rays have the same range R, and we shall consider three different possible values of this range:

I. $R<2.5$ cm of lead (thickness of shield on counter 3).
II. $R>20$ cm of lead (thickness of absorption screen).
III. 2.5 cm of lead $<R<20$ cm lead.

If we confine our attention to the triple coincidences, there are four possible ways in which coincident impulses may be produced. These are:

1. A single β traverses counters 1, 2 and 3.
2. β_1 traverses 1 and 2, while β_2 traverses 3.
3. β_1 traverses 1, while β_2 traverses 2 and 3.
4. β_1 traverses 1, β_2 traverses 2, and β_3 traverses 3.

Possibility 1 represents a single β-particle of high range setting off all three counters. Coincidences due to pairs, showers and bursts of ions are represented by possibilities 2, 3 and 4.

Table III summarizes, for cases I, II and III and 1, 2, 3, and 4, the predicted values of B/C, where B represents the coincidence rate with the absorbing block between counters 1 and 2 and C the rate with the absorber above the counters. In this table, we assume that 20 cm of lead reduces the number of traversing β's by a factor K. Due to the passage of the photons and the incident β's through the lead, secondaries are emitted from its lower side which are m times the number of β's striking the upper side. The total emergent β's are then $L=K+m$ times as many as the incident β's. Usually $L<1$; but always $L>K$ except when $m=0$, which would mean no secondaries due to photons. Thus for cases I and III, $K=0$ and $L=m$; for the case II, $0<K<L$. In calculating the ratio B/C in case II we note that since the range of the β's is greater than 20 cm, they will probably originate at a distance above the counters about equal to the air equivalent of 20 cm of lead, i.e., about 2 km away. Thus without the lead absorber above the counters it is highly improbable that more than one particle originating at such a distance will strike the counter tubes. The same argument applies with somewhat less weight to case III, but not necessarily to case I.

Examination of Table III will show that of the 12 imagined types of coincidences only those

TABLE III. *Summary of predicted values of B/C under various assumptions.*

Possibilities for triple coincidences	I	II	III
	$R<2.5$ cm Pb	$R>20$ cm Pb	$2.5<R<20$ cm Pb
1. β through 1, 2, 3	$B/C=K/(K+m)=0$	$B/C=K/(K+m)<1$	$B/C=K/(K+m)=0$
2. β_1 through 1, 2 β_2 through 3	$(B/C)_1=K/(K+m)=0$ $(B/C)_2\sim 1$ $(B/C)_1(B/C)_2\doteq 0$	$(B/C)_1=K/(K+m)<1$ $(B/C)_2\sim 0$ because β_1 originates far away in exp. B $(B/C)_1(B/C)_2\doteq 0$	$(B/C)_1=K/(K+m)=0$ $(B/C)_2\ll 1$ (Distant origin of β_1) $(B/C)_1(B/C)_2=0$
3. β_1 through 1 β_2 through 2, 3	$(B/C)_1=1/m>1$ $(B/C)_2=0$ (can't penetrate tube 3) $(B/C)_1(B/C)_2=0$	$(B/C)_1=1/L>1$ $(B/C)_2\sim 0$ same reason as above $(B/C)_1(B/C)_2\sim 0$	$(B/C)_1=1/m>1$ $(B/C)_2\ll 1$ same reason as above $(B/C)_1(B/C)_2\ll 1$
4. β_1 through 1 β_2 through 2 β_3 through 3	$(B/C)_1=1/m>1$ $(B/C)_2\sim 1$, if origin of β_1 is from tube 1, otherwise $\ll 1$ $(B/C)_3\sim 1$ same reason as above $(B/C)_1(B/C)_2(B/C)_3\sim 1$	$(B/C)_1=1/L>1$ $(B/C)_2\sim 0$ same reason as above $(B/C)_3\sim 0$ same reason as above $(B/C)_1(B/C)_2(B/C)_3\sim 0$	$(B/C)_1=1/m>1$ $(B/C)_2\ll 1$ same reason as above $(B/C)_3\ll 1$, same reason as above $(B/C)_1(B/C)_2(B/C)_3\ll 1$

characterized as *I 4* and *II 1* are capable of giving the observed result of B/C almost equal to 1. These we now examine in further detail.

In case *I 4* the photon must traverse the lead shield about counter 3, since the β-ray which it emits is incapable of passing through the shield. The photon must, however, have already produced two β's which will have entered counters 1 and 2. If in experiment B, with the lead between counters 1 and 2, the probability of a β-ray passing through tube 1 is to be comparable with that for C when the lead is directly over counter 1, the probable origin of the first β-particle must be only a very short distance above the first counter. This condition cannot be fulfilled if the range of the β's is much greater than the thickness of the counter tube wall. Case *I 4* is thus satisfactory only if the photon has a high probability of producing a separate β-ray which will ionize the gas in each counter traversed. That is, the photon itself acts as an ionizing particle.

This is identical with the conclusion required by Johnson and Street's[12] experiment, with counters similarly arranged, by comparing the triple coincidences with doubles in counters 1 and 3. His results indicated that if the triple coincidences are due to secondary β-rays produced by photons, there must *always* be a β-ray passing through the counter traversed by the photon. Such an action by a photon is so contrary to our knowledge of the catastrophic nature of β-particle production by photons, either as photo- or recoil-electrons, that it seems justifiable to rule out this possibility.

We have noted above that the observed ratio of $B/C=0.94$ can be accounted for in terms of penetrating ionizing particles traversing all three counters, with an occasional production of secondaries in experiment C traversing counters 1 and 2. This interpretation will still hold if, as in case *II 1*, the β-particles are produced by photons in the atmosphere above the apparatus. If, however, any appreciable fraction of these penetrating β-rays are produced by the photons traversing the lead, B/C should be markedly less than 1. If all the coincidences were due to penetrating β-particles produced in the lead, counter 1 would receive no β's in case B, so B/C should be 0. From the observed ratio 0.94 we can say that less than six percent, if any, of the coincidences in experiment C are due to penetrating secondaries produced by photons in the lead absorber.

For highly penetrating photons passing through the atmosphere, equivalent to about 90 cm of lead, and then through 20 cm of lead directly over the counting tubes, much more than six percent of the β-particles reaching the tubes should originate in the lead absorbers. The small β-ray production in the lead might, however, be interpreted by supposing that

[12] T. H. Johnson and J. C. Street, Phys. Rev. **42**, 144 (1932).

photons had been more than 94 percent absorbed in the atmosphere before reaching the apparatus, whereas, the resulting β-particles were more penetrating than the parent photons. We thus reach what seems to be the only permissible photon interpretation of this experiment, namely, that the photons themselves are almost or completely absorbed in the atmosphere above the apparatus, but produce β-particles more penetrating than the photons which cause the observed coincidences. This experiment cannot distinguish such penetrating secondary β-particles if unaccompanied by their parent photons, from primary β-rays coming from above the atmosphere.

Absorption of Coincidence Particles

Comparison of the absorption of the coincidence-producing particles with that of cosmic rays as measured in ionization chambers shows that these absorptions are nearly the same, thus supporting the conclusion of earlier workers that the radiations measured by the two methods are of fundamentally the same nature.

From the usual absorption coefficient formula,

$$\mu=(1/x)\log(I_0/I), \tag{1}$$

where x is the thickness of the absorbing screen, and I_0/I is the ratio of the counting rate without to that with the screen, and by assuming in each case the absorbing block between tubes 1 and 2, where secondaries are of least importance, we get for the double coincidences,

$$\mu_{\mathrm{Pb}2}=24\times10^{-3}\text{ per cm} \tag{2}$$

and for the triple coincidences,

$$\mu_{\mathrm{Pb}3}=16\times10^{-3}\text{ per cm.} \tag{3}$$

Kolhörster and Tuwim[13] give the following relation between the absorption coefficients of cosmic rays in different substances:

$$\frac{\mu_{\mathrm{H_2O}}}{\mu_{\mathrm{Pb}}}=\frac{\rho_{\mathrm{H_2O}}(Z/A)_{\mathrm{H_2O}}}{\rho_{\mathrm{Pb}}(Z/A)_{\mathrm{Pb}}}. \tag{4}$$

Here ρ is the density (10.6 g/cc in these experiments) and Z and A are the atomic number and weight, respectively. Thus we find,

$$\mu_{\mathrm{H_2O}}=0.142\mu_{\mathrm{Pb}}$$

or

$$=3.2\times10^{-3}\quad\text{(doubles)} \tag{5}$$
$$=2.2\times10^{-3}\quad\text{(triples).}$$

To compare the values for the absorption coefficient thus obtained with that from ionization chamber measurements, we calculate first the intensity supposing that the radiation enters normally into the atmosphere. This is given by Gross'[14] transformation,

$$\psi=I-PdI/dP,$$

where ψ is the intensity for rays coming vertically through the atmosphere I is that as observed from all directions, and P is the barometric pressure. The absorption coefficient is then determined graphically from the ψ *vs.* P curve from the relation,

$$\mu=d\psi/\psi dP.$$

From the values of I *vs.* P collected by Eckhart[15] we thus find for the absorption in water at a depth of 11.5 meters, the equivalent of the atmosphere plus half of the 20 cm lead absorber,

$$\mu=1.90\times10^{-3}\text{ cm}^{-1}\quad\text{(ionization).} \tag{6}$$

The agreement between this value for μ and that from the triple counter method where secondaries play a minimum rôle, is as close as can be expected in view of the difference in procedure, and indicates that the rays responsible for the coincidences are the same kind as those measured with ionization chambers. This supports the findings of Bothe and Kolhörster and of Rossi. We have shown, however, that the coincidences here studied are due to ionizing particles of high penetrating power. The close agreement of their absorption coefficients is thus most readily interpreted on the view that the cosmic rays observed with ionization chambers likewise consist of ionizing particles.

It gives me great pleasure to acknowledge my indebtedness to Professor A. H. Compton for the suggestion of the problem and for his constant inspiration and helpful advice throughout the investigation. I wish also to express my thanks to The Rockefeller Foundation for the Fellowship that enabled me to work on this problem.

[13] W. Kolhörster and L. Tuwim, Physikalische Probleme der Hohenstrahlung, 148 (1934).

[14] B. Gross, Zeits. f. Physik **83**, 214 (1933).

[15] C. Eckhart, Phys. Rev. **45**, 851 (1934).