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Shower-Producing Cosmic Rays

The ejection of several particles from a material by a cosmic ray corpuscle has been called a "shower" by the early workers, Johnson,¹ Rossi,² and others. In a previous paper³ we have shown that the shower particles are produced by light element secondaries and so are tertiary particles. With the usual arrangement of counters in a triangle we have investigated the secondaries from aluminum.⁴ We compared these results with those obtained from work in air by Funfer⁵ and Rossi.

We obtained $.7 \text{ cm}^{-1} \text{ Pb}$ for the absorption coefficient of aluminum secondaries and $.32 \text{ cm}^{-1} \text{ Pb}$ for that of air secondaries. We also obtained $.5 \text{ cm}^{-1} \text{ Pb}$ for that of the materials of our roof ³and air.

Now we have investigated the properties of the secondaries from paraffin wax. The apparatus was arranged as in Fig. 1.

The Geiger counters are cylinders 4.8 cm in diameter and 20 cm long containing argon. They have ²⁰⁰a cylinder of copper, and a fine tungsten wire for the central electrode and are sealed in glass at a pressure of 3 cm Hg. The triple coincidences were recorded with the same amplifier ~~is~~ used in previous work. The lead scatterer, S, was 10 cm wide and 30 cm long. The paraffin block was 12 cm wide and 32 cm long.

First, with this arrangement the thickness of the lead scatterer was kept constant. The thickness chosen was 0.85 cm which gives about the maximum number of showers produced

FIGURE 1

by aluminum or air secondaries. The thickness of the paraffin block was varied and the results are contained in Table I.

Table I

Thickness of Paraffin (cm)	Total Count	Time (hours)	Counting Rate (counts per hour)
0	430	33.9	12.7
6.5	353	21.8	16.2
13.0	285	15.7	18.2
19.5	304	16.4	18.5
26.0	302	16.1	18.7
31.5	320	17.2	18.6
38.0	864	47.4	18.2

In this table the count with no paraffin is due to secondaries from air and the materials of the roof. With increasing thicknesses of paraffin wax the number of paraffin secondaries increases until an equilibrium is set up with the primaries. At the same time the secondaries from the roof are absorbed in the paraffin. Then, after equilibrium between the primaries and the paraffin secondaries has been reached, the count begins to decrease with the absorption of the primaries in the paraffin.

The results of Table I have been plotted in the curve of Fig. 2. The count with no paraffin has been taken as the zero ordinate and the curve shows the increase ~~of the number of tertiary~~ due to paraffin secondaries. The increase of the number of tertiaries due to paraffin secondaries over the number due ~~due~~ to secondaries from the roof and air may be due to one or more of several reasons: (1) The secondaries from paraffin

may be more efficient in producing showers. (2) The number of secondaries in equilibrium with primaries may be greater for paraffin than for the materials of the roof. (3) There may be a neutron component which is very efficient in ejecting secondary protons from the paraffin.

The third reason for this increase is somewhat invalidated by negative results of attempts to detect neutrons in the cosmic ray showers with closed chambers, particularly in those of Blackett.⁶ Also the fact that we observed more tertiaries from aluminum secondaries than the ordinary secondaries indicates one or both of the first two reasons.

With the same arrangement of apparatus, the paraffin block was kept at a constant thickness of 38.0 cm and the thickness of S was varied. The results are shown in Table II.

Table II

Thickness of Pb Scatterer (cm)	Total Count	Total Time (hours)	Counting Rate (counts per hour)
0	339	20.0	16.9 $\pm$.6
0.37	389	19.4	20.0 $\pm$.7
0.55	311	12.8	24.3 $\pm$.9
0.64	437	16.8	26.1 $\pm$.8
0.87	331	12.5	26.6 $\pm$.9
0.96	864	35.1	24.6 $\pm$.6
1.13	327	13.9	23.5 $\pm$.9
1.4	273	12.6	21.7 $\pm$.9
2.6	268	14.6	18.4 $\pm$.9
3.7	411	25.7	16.0 $\pm$.5
4.1	302	20.0	15.2 $\pm$.6
7.0	296	23.7	12.5 $\pm$.5
8.8	253	22.6	11.2 $\pm$.5

It can be seen from these results that the number of tertiaries increases to a maximum and then falls off exponentially. Similar results with secondaries from the roof suggest-

FIG. 3

ed the secondary-tertiary theory prepared by the writer in (3). We obtained ~~the~~ for the number of tertiaries, n_t , the result

$$n_t = K \mu_s e^{-\mu_s l} \left(\frac{1 - e^{-l(\mu_t - \mu_s)}}{\mu_t - \mu_s} \right) \quad (1)$$

where K is a constant, μ_s is the absorption coefficient of the secondaries in cm^{-1} Pb, l is the thickness of the scatterer, S , in cm Pb, μ_t is the absorption coefficient of the tertiaries in cm^{-1} Pb and e is the base of natural logarithms. From the results obtained in Table II it is possible to calculate the two required ~~constants~~ absorption coefficients,

Making use of the results of Table II we plotted the curve of Fig. 3 and obtained the constants from the curve. We find that μ_s , the absorption coefficient of the paraffin secondaries is $.85 \text{ cm}^{-1}$ Pb. The absorption coefficient of the lead tertiaries ejected by paraffin secondaries is found to be 1.9 cm^{-1} Pb.

Due to the sharp maximum the curve ^{is} difficult to fit, but the values given are the best obtainable. The probable errors due to statistical variations have been plotted as vertical lines thru the points of Fig. 3. The equation (1) with the above constants agrees with this curve within these limits.

The sharp high maximum in the curve of Fig. 3 is difficult to explain. It seems to indicate the presence of neutrons in the cosmic ray beam. However, the height of the maximum may be due largely to experimental or ~~statistical~~ statistical error. This explanation also seems probable since the maximum occurs at about .8 cm lead which agrees well with the previous result of .9 cm lead for tertiaries from aluminum secondaries.

It is interesting to compare the results on paraffin secondaries and their lead tertiaries with those of other materials. For this purpose we have assembled Table III.

Table III

Material	μ_s (cm^{-1} Pb)	μ_t (cm^{-1} Pb)
1. Roof and Air	.50	2.58
2. Aluminum	.70	2.0
3. Paraffin	.85	1.9
4. Air (Rossi's and Funfer's results)	.32	1.18

In our three results 1, 2, 3, we see that all the secondaries have a decidedly lower absorption coefficient than any of the tertiaries. It follows that the secondary particles are of higher energy than the tertiary showers. The last values (4) are calculated from results of other workers. The absorption coefficient of the secondaries keeps increasing from .50 to .85 cm^{-1} Pb. This seems the result of higher and sharper maxima, that for the roof and air being the lowest and broadest and for paraffin the highest and sharpest. The absorption coefficient of the tertiaries is practically the same for paraffin and aluminum. This is probably due to the maximum occurring at very near the same thickness of scatterer for these two materials. The maximum for the secondaries from the air and roof is at a ~~smaller~~ smaller thickness of lead hence the greater absorption coefficient of their lead tertiaries.

In order to study the particles which produce the paraffin secondaries, a lead absorber was placed above the paraffin as

FIGURE 4

shown in Fig. 4. This lead absorber removed the primaries from the cosmic ray beam gradually as the thickness was increased. The dimensions of the lead absorber were 18 cm by 40 cm and the thickness was varied. The paraffin block was maintained at a thickness of 32.5 cm and the scatterer at a thickness of 0.85 cm.

With this apparatus the counting rate with a lead absorber 5.3 cm thick^k was determined. The paraffin block was removed and the count was obtained again. It was found that removing the block of paraffin decreased the counting rate from 22.5 per hour to 20.3 per hour. This indicates that there was some sort of secondary radiation from the paraffin which caused triple coincidences. Also the lead scatterer, S, was removed and the count decreased below 20 per hour. This shows that the secondary particles from the paraffin were very probably producing tertiary showers in the lead scatterer.

Using this arrangement counts were made with different thicknesses of the lead absorber. The results are shown in Table IV.

Table IV

Thickness of Pb absorber (cm)	Total Count	Time (hours)	Rate (counts/hour)	Corrected Rate (counts/hour)
0	563	22.1	25.9	-
1.3	460	19.7	23.4	-
3.3	425	17.1	24.9	20.8
5.3	336	14.2	23.6	19.7
6.3	425	18.4	23.1	19.3
7.0	531	27.7	19.1	
9.3	410	18.5	22.2	18.5
11.0	224	12.3	18.2	

FIG 5

In the data of Table IV some of the values have been corrected. In rerunning the points it was found that the count with no lead absorber had changed. This showed that the sensitivity of the apparatus had probably changed; so the second set of values was corrected. This correction was simply changing all counts in the ratio of the initial rate with no lead absorber to the final rate with no lead absorber.

The corrected values of Table IV have been plotted in the curves of Fig. 5. It will be noted that all the points fall fairly well on the curve. The correction which was applied probably does not have an error greater than the statistical error.

We assume that the absorption obeys an exponential law

$$I = I_0 e^{-\mu_p x} \quad \dots (2)$$

Where the shower intensity at a thickness of absorber, x , is I and at $x=0$ is I_0 . The constant μ_p is the absorption coefficient of the primary radiation. If we denote the observed values for a thickness x_n in Table IV by C_n , then we have

$$(C_n - K) = I_0 e^{-\mu_p x_n} \quad \dots (3)$$

where K is a constant. From observed values at two thicknesses we eliminate I_0

$$\frac{(C_1 - K)}{(C_2 - K)} = e^{-\mu_p (x_1 - x_2)} \quad \dots (4)$$

With another equation of the type (4) with different observed values we can solve for the constant K which must be subtracted from the observed counting rates. The value of this constant was found to be 17.0 which is about the chance count with no materials near the counter.

After the subtraction of this constant the logarithms of the corrected values were plotted against the thickness.⁷ The points fell nearly on a straight line. None of the points were further from the straight line than the statistical error. The slope of the line gives the absorption coefficient $.175 \text{ cm}^{-1} \text{ Pb.}$

The absorption coefficient of the shower producing radiation has been found by several workers. Johnson⁸ measured the shower intensity at several altitudes and found the shower-producing radiation had the absorption coefficient $0.50 \text{ m}^{-1} \text{ H}_2\text{O.}$ This agreed well with his absorption coefficient for the soft corpuscular component of cosmic ray primaries. Tater, Montgomery⁹ found from measurements at different altitudes a value $0.90 \text{ m}^{-1} \text{ H}_2\text{O.}$ Pickering¹⁰ made measurements under three thicknesses of water and the absorption coefficients calculated roughly from his values agrees fairly well with Montgomery's value.

If we assume mass absorption for these shower producing primaries the absorption coefficient is directly proportional to the density. Then, Montgomery's data correspond to an absorption coefficient of $0.10 \text{ cm}^{-1} \text{ Pb.}$ This value is much smaller than the result we obtained for the absorption coefficient.

In order to investigate this disagreement between our results and those of Montgomery and Pickering, the absorption in a light element was measured. The apparatus was again arranged as in Fig. 1 but the paraffin block was replaced

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with an aluminum one. The dimensions of this aluminum block were 13 cm wide by 36 cm long with a variable thickness.

The results of three counts are given in Table V.

Table V

Thickness of Al Block (cm)	Total Count	Time (hours)	Rate (counts/hour)
15.5	644	21.0	30.6
20.6	248	8.5	29.2
25.7	687	23.9	28.7

The first thickness used in this experiment is sufficient to absorb all the ordinary secondaries and produce the equilibrium amount of aluminum secondaries. That is, the first value is past the maximum of a curve for aluminum similar to that of Fig. 2 for paraffin. The decrease in count is due to the absorption of the primary particles; so we can obtain an absorption coefficient for the shower-producing radiation. This quantity was found to be $0.022 \text{ cm}^{-1} \text{ Al}$.

If we assume a mass relation this result agrees very well with those of the other workers. Our value gives $0.82 \text{ m}^{-1} \text{ H}_2\text{O}$ to compare with their $0.90 \text{ m}^{-1} \text{ H}_2\text{O}$. If reduced to $\text{cm}^{-1} \text{ Pb}$ our value obtained for the absorption coefficient of the primaries in aluminum gives $.091 \text{ cm}^{-1} \text{ Pb}$. This value is considerably less than the value obtained for absorption of the primaries in lead, $.175 \text{ cm}^{-1} \text{ Pb}$.

A comparison of our results on aluminum and other workers' results shows that for light elements the absorption does seem to follow a mass law. However, our value for lead is consider-

FIG 6

ably higher than the value predicted on the mass law from the other results. This high absorption in lead has been observed by most cosmic ray workers.

In order to investigate the differences, we determined the absorption in iron, which has an atomic number intermediate between aluminum and lead. The arrangement of Fig. 4 was used in these measurements. The aluminum block 15.5 cm thick, 30 cm long, and 13 cm wide was used as a source of secondaries. The iron absorbers, which replaced the lead absorbers of Fig. 4, were 25 cm wide and 61 cm long.

The counting rates were determined for different thicknesses of iron and the results are given in Table VI.

Table VI

Thickness of Fe Absorber (cm)	Total Count	Time (hours)	Rate (counts/hour)
0	256	8.7	29.5
1.20	204	7.4	27.6
2.54	370	14.7	24.9
5.08	297	12.6	23.5
7.65	381	18.3	20.8
10.28	545	28.2	19.3
12.82	253	14.2	17.9
15.34	495	29.0	17.0
17.88	417	24.7	16.9

These results have been plotted in the curve of Fig. 6. In order to test the exponential character of the absorption we plotted the logarithms of the values of Table VI after the subtraction of a constant calculated as above for lead absorption. The resulting curve is given in Fig. 7. It will be

FIG 7

noted that the points lie on the straight ^{line} even out to the ~~greater~~ ^{greater} thickness of iron. The slope of this curve gives the absorption coefficient of $\mu_p = .137 \text{ cm}^{-1} \text{ Fe}$.

In order to compare this value with the results on lead and aluminum, we assume mass absorption as before. The absorption coefficient in iron corresponds to $.195 \text{ cm}^{-1} \text{ Pb}$. This value agrees fairly well with the $.175 \text{ cm}^{-1} \text{ Pb}$ value found for lead. Thus it appears that the absorption in iron and lead do obey a mass relation.

This result seems to invalidate the explanation ascribing the differences between absorption in aluminum and lead to a variation of the absorption coefficient with some power of the density greater than one. Another possible explanation is that the difference of arrangements in the two cases might account for the disagreement of absorption coefficients. This difference in arrangement may be seen from a comparison of Fig. 4 and Fig. 1. In our experiments on aluminum, also in those of other workers on light elements, the light material, which produces the secondaries causing the showers, is used as an absorber of the primaries. On the other hand the experiments with heavy elements make use of a constant amount of light material beneath to produce the secondaries. In order to test this explanation an experiment was carried out with the arrangement of Fig. 4 but with a light material, water, as the absorber. The same block of aluminum as that of above experiments was used to produce secondaries and two large tanks of water were placed side by side ~~above this~~

FIG 8

above this block as absorbers. The tanks were each 21 cm wide and 61 cm long and the depth of water was varied to determine the absorption.

The results are given in Table VII.

Table VII

Thickness of H_2O Absorber (cm)	Total Count	Time (hours)	Rate (counts/hour)
15.0	432	17.0	25.4
25.4	490	20.4	24.0
40.0	376	16.8	22.4
57.0	488	23.5	20.8
71.0	309	15.5	20.0
90.5	203	10.6	19.2
115.1	518	28.0	18.5

The results of Table VII have been plotted in the curve of Fig. 8. It is evident that the points fall on a smooth exponential curve so the log curve was not plotted. The constant to be subtracted from the values of Table VII to give the true intensity of showers was calculated in the usual way. The absorption coefficient of the primaries producing aluminum secondaries was found to be $1.83 \text{ m}^{-1} H_2O$.

This result agrees within the limits of error with the value predicted by the mass law from results on iron and lead. The value for aluminum therefore disagrees with all our other values. The absorption coefficients for the four materials are given in Table VIII.

Count per Hour

FIG 9

32

31

30

29

28

27

26

25

0

1

2

3

4

5

Thickness of Absorber in Cm

Table VIII

Absorber	μ_p in cm^{-1} of absorber	μ_p in . 100^{-1} grams/ cm^2
H_2O	.0183	1.83
Fe	.136	1.74
Pb	.175	1.56
Al	.022	.83

The first three results for the mass coefficient agree fairly well. The value with lead was obtained with the paraffin block as the source of secondaries and the others with the aluminum block.

We therefore repeated the experiment with lead as absorber using the same block of aluminum employed in the iron and lead experiments. The results of this experiment are given in Table IX.

Table IX

Thickness of Pb Absorber (cm)	Total Count	Time (hours)	Rate (counts/hour)
0	361	11.4	31.6
1	247	8.2	30.1
2	686	24.2	28.3
3	492	17.8	27.6
5	458	16.6	26.5

The results have been plotted in the curve of Fig. 9. The constant to be subtracted ~~to be~~ was calculated in the usual way and the logarithmic curve plotted. The points fell on a straight line within the statistical error. The absorption coefficient was determined from the slope of the straight

14
7
line as $.197 \text{ cm}^{-1} \text{ Pb}$. This gives for the mass coefficient $.174$ which is in much better agreement with the values for iron and water.

The values we have obtained for the absorption coefficients of the primaries are much smaller than the absorption coefficients of the secondary rays. The values of $.197 \text{ cm}^{-1} \text{ Pb}$ and $.175 \text{ cm}^{-1} \text{ Pb}$ are several times smaller than the values $.7$ for aluminum secondaries and $.25$ for wax secondaries. The secondaries which actually produce the showers, must therefore be of much lower energy than the primary rays. This ~~keeps~~ helps to confirm the assumption that the showers are tertiary particles.

In conclusion I wish to thank Professor H.A. Wilson for many helpful suggestions and valuable interviews in the course of this work.

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The Secondary and Tertiary Particles Produced by Cosmic Rays

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Cosmic-ray secondaries and tertiaries have been studied in a series of experiments. It has been shown that the secondaries from lead have little power to produce detectable tertiaries or showers from lead or aluminum. The secondaries from aluminum have been found to produce more showers in lead than the secondaries from air. The absorption coefficient of the secondaries from aluminum has been found to be $0.7 \text{ cm}^{-1} \text{ Pb}$ and the absorption coefficient of their lead tertiaries $2.0 \text{ cm}^{-1} \text{ Pb}$. The values for secondaries from air and a heavy roof, and their lead tertiaries were previously found to be $0.5 \text{ cm}^{-1} \text{ Pb}$ and $2.58 \text{ cm}^{-1} \text{ Pb}$. The values obtained from Rossi's and Funfer's

data are $0.32 \text{ cm}^{-1} \text{ Pb}$ for the air secondaries and $1.18 \text{ cm}^{-1} \text{ Pb}$ for their lead tertiaries. It follows that the air secondaries and their lead tertiaries have greater energies than the aluminum secondaries and their lead tertiaries. It has been found that a component of the cosmic rays even softer than the corpuscular component is probably the chief source of the secondaries producing the showers. There is some evidence that non-ionizing particles produce a portion of the showers and that possibly non-ionizing secondaries are produced in lead and that these particles can produce ionizing particles in aluminum.

THIS paper contains an account of experiments on the production and absorption of cosmic-ray secondary and tertiary particles. It follows the work of a previous paper.¹ The results of these new experiments and those of other workers, B. Rossi,² Funfer,³ Ackemann⁴ and Hummel,⁵ help to confirm the assumptions made and the theory proposed in the previous paper.

If we place an absorbing layer of lead in the path of the cosmic-ray primaries and secondaries, we obtain tertiary rays produced by the absorption of the secondaries. At the same time the primary cosmic rays produce secondary particles in the lead. These lead secondary particles are strongly absorbed. After a certain thickness their number reaches a constant ratio with the number of primaries.

In the previous paper the number of tertiary particles ejected by cosmic-ray secondaries from an absorbing layer was shown to be given by the equation

$$\bar{n}_t = K\mu_s e^{-\mu_s l} \left[\frac{1 - e^{-l(\mu_t - \mu_s)}}{\mu_t - \mu_s} \right]. \quad (1)$$

Here n_t is the number of tertiaries emerging from the bottom of a layer of thickness, l , K is a constant, μ_s is the absorption coefficient of the secondaries, and μ_t is the absorption coefficient of the tertiaries. A similar result was obtained at the same time by Bhabha.⁶

The violent bursts of ejected particles, Hoffmann Stösse, produce triple coincidences in the usual arrangement shown in Fig. 1. The Stösse, however, are rare events in comparison with the frequent production of tertiary particles. Messerschmidt⁷ has shown that the number of Stösse per

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FIG. 1.

FIG. 2.

FIG. 1. Diagram of usual cosmic-ray apparatus for investigating showers.

FIG. 2. Arrangement for investigating lead secondaries.

hour from a large mass of material is only about 0.5 to 1.0. This is certainly small in comparison with the production of tertiaries at a rate usually as high as 10 or more per hour. Also the number of Stösse is roughly proportional to the amount of material present, hence in the present experiments, where usually small amounts of absorbers are used, the number of Stösse is much smaller than 0.5 to 1 per hour and so the Stösse can be neglected.

The lead secondaries are assumed to be projected in an almost straight-ahead direction so that they could not produce triple coincidences in a counter arrangement similar to Fig. 1. This assumption was experimentally verified in (1). A beam was defined by two counters and a search with a third counter was made for secondaries produced in a large lead block. No secondaries were found at any angle hence they must have been projected in a straight-ahead beam. We neglected in (1) the possibility that these secondaries of the absorbing material might produce a portion of the tertiary particles by their absorption in the same material. In most experiments the absorbing material is lead so we have made an experimental test for lead tertiaries produced by lead secondaries.

The apparatus used in these experiments is essentially the same as that used in (1). The three Geiger counters are 4.8 cm in diameter and 20 cm effective length. They contain argon at 3 cm pressure and operate at about 2000 volts. They are connected to the usual selecting amplifier with a thyratron counting circuit.

The arrangement of Fig. 2 was used for this test for lead tertiaries produced by lead secondaries. A large block of lead 7 cm thick, 14 cm

wide and 40 cm long above the counters cut out the air secondaries in the solid angle defined by the counters and replaced them with lead secondaries. These pass through the top counter and fall on the scattering layer *S* where they are absorbed with the production of tertiaries.

With this arrangement, counts were made with the lead block in and with or without the scattering layer *S*. A count was also made with *S* in and the block removed so that the air secondaries produced tertiaries in *S*. From the results shown in Table I, we see that the tertiaries

TABLE I.

<i>S</i>	0.63 cm Pb	0.16 cm Pb	0.63 cm Al	0.32 cm Al
COUNTING RATE WITH Pb BLOCK AND <i>S</i>	4.10 ± 0.17	3.5 ± 0.25	4.3 ± 0.20	4.4 ± 0.21
COUNTING RATE WITH Pb BLOCK ALONE	4.02 ± 0.19	3.3 ± 0.20	4.2 ± 0.18	4.5 ± 0.22
COUNTING RATE WITH <i>S</i> ALONE	6.94 ± 0.24	4.76 ± 0.18	4.33 ± 0.20	4.7 ± 0.17

produced in *S* by the lead secondaries do not affect the count.

The lead secondaries have lower energy than light element secondaries and their lead tertiaries have still lower energies. This is evident from a consideration of the absorption coefficients: For air secondaries, 0.32 cm⁻¹ Pb (calculated later); for aluminum secondaries, 0.7 cm⁻¹ Pb (also obtained later). Hence, the absorption coefficient of the lead secondaries is much greater and the corresponding energy is much smaller than the energy of light element secondaries. Hence only a very small number of these tertiaries get out of the lead. These are probably absorbed in the counter walls or in the steel cylinder which shields the counters from electrical disturbances. Hence they do not affect the count.

An experiment was performed to test the assumption that tertiary particles are produced by light element secondaries. For this purpose a block of aluminum 15.5 cm thick, 13 cm wide and 36 cm long was substituted for the lead block in Fig. 2. This thickness of aluminum is sufficient to absorb all the air secondaries. Also it replaces them with the equilibrium amount of aluminum secondaries.

Runs were made with lead scatterers of various thicknesses, with and without the heavy aluminum block. Sample results are shown in Table II. The increase with the aluminum block over the

TABLE II. Counting rate with and without aluminum block with various thicknesses.

LEAD THICKNESS	COUNTING RATE	
	WITH AL BLOCK	WITHOUT AL BLOCK
0.32 cm	10.7 ± 0.3	7.5 ± 0.6
0.47 cm	14.9 ± 0.8	9.2 ± 0.7
0.63 cm	13.6 ± 0.7	11.5 ± 0.7
1.9 cm	10.4 ± 0.4	8.1 ± 0.6

counters indicates a higher equilibrium value of secondaries from aluminum than from the materials of the roof and the air ordinarily above the counters. It is also possible that aluminum secondaries are more efficient in producing lead tertiaries than air secondaries are, or a combination of the two processes may be the correct explanation.

It will be noted that the counting rate has increased in Table II. This change is due to a change in the counters themselves. From time to time during the course of these experiments, it was found necessary to change the gas in the counters and hence to change their counting rate.

The sources of error, other than that due to statistical fluctuations, are those generally found with Geiger counters and coincidence circuits. One source of error is variation in the counting rate of the counters. The causes of any such variation are usually voltage fluctuations in the high tension and leakage at the condenser-high resistance coupling to the first tube. This latter was minimized even for adverse weather conditions by coating with cerosin, a wax with high resistance to surface leakage. The high tension is taken from a rectifier whose a.c. input is regulated with a voltage regulator. The output voltage was constant to ± 15 volts as checked by a 3 megohm leak and a milliammeter over a long period. This voltage fluctuation is not sufficient to alter appreciably the counting rate.

The next source of error is due to the fact that the triple coincidence selector does not function perfectly. Changes in the efficiency of the circuit due to plate voltage fluctuations were reduced by floating the B battery with a rectifier so that no current was drawn out of the battery. Filament battery voltages were also kept within restricted ranges. However, there might have been some variation in the screen voltage since the current to the screens was not balanced out.

FIG. 3. Absorption-in-lead curve for aluminum secondaries.

Finally, the apparatus was checked from time to time for long period fluctuations by observing the chance count. This chance count over such periods was found to be constant within the statistical error of the rates obtained in the experiment. Hence, we conclude that long period fluctuations are negligible compared to the statistical error. However, there are probably short period fluctuations which are at least as great as the statistical fluctuation due to a finite count.

The thickness of the lead scatterer was varied with the aluminum block over the top counter. The results are plotted in the curve of Fig. 3. It is interesting to note that the curve shows some evidence of a small second maximum. This second rise in the curve occurs at large thicknesses of lead. This doubtful maximum is in accord with the results of Ackemann⁴ and of Hummel⁵ with two horizontal counters arranged side by side. However, their maxima are much more pronounced. This difference indicates that the particles causing this second increase are in the main uncharged. For if the particles are uncharged, the top counter of the apparatus would not be set off unless a charged particle was ejected from the counter walls. However, in the arrangement of Ackemann and Hummel both charged and uncharged particles can eject charged lead tertiaries into their two counters to produce coincidences.

There has been some indication of the presence of uncharged secondaries in other work. This point we discuss later. The character of the particles producing this second maximum is being investigated.

FIG. 4. Calculated absorption curve for aluminum secondaries with experimental points plotted.

From the data of Fig. 3 by means of Eq. (1) we can calculate the absorption coefficients. The absorption coefficient of the lead tertiaries produced by the aluminum secondaries is found to be $2.0 \text{ cm}^{-1} \text{ Pb}$. The absorption coefficient of the aluminum secondaries in the lead is $0.7 \text{ cm}^{-1} \text{ Pb}$. The curve obtained from these two calculated absorption coefficients is shown in Fig. 4. The experimental values are plotted on this curve as circles and the statistical errors as the length of the vertical lines through the circles.

Funfer² and Rossi³ have done the most extensive work with Geiger counters on absorption of cosmic-ray particles. Funfer's arrangement is that of Fig. 1 and Rossi's is shown in schematic diagram in Fig. 5. Rossi's curve for the variation of the triple coincidence count with the thickness of S does not agree with Funfer's curve. However, in Rossi's arrangement it is evident that pairs of particles at small angles may produce triple coincidences. This difference is partly due to the bottom counter being twice the size of the other two counters. An example of this is shown in the two ray paths drawn dotted in the figure.

In Fig. 6 Rossi's and Funfer's curves are given and the difference is plotted as the dotted curve.

FIG. 5. Rossi's arrangement for investigating air secondaries.

These two curves are reduced to a common basis by considering their respective chance counts, which are a criterion for the sensitivity of the apparatus. Rossi's chance count is approximately twice Funfer's so the ordinate scale of Rossi is made twice that of Funfer. This amounts to plotting the two curves as fractions of the chance counts and the difference curve is obtained in the same way. This difference is due partly to the above property of Rossi's apparatus and partly to the fact that he had heavy blocks of lead protecting the counters at the sides and bottom. These blocks of lead should produce an increase similar to the dotted curve. In fact, Funfer has placed heavy lead blocks at the sides of and beneath his counters and found a very similar increase of the counting rate over that with no protecting blocks. The difference between Rossi's and Funfer's curves is no doubt due to the presence of the heavy lead blocks in Rossi's experiments. Therefore, we have computed the absorption coefficients from Funfer's curve. The

FIG. 6. Rossi's and Funfer's experimental results.

absorption coefficient of air secondaries is found to be $0.32 \text{ cm}^{-1} \text{ Pb}$, and the absorption coefficient of the lead tertiaries produced by these secondaries is found to be $1.18 \text{ cm}^{-1} \text{ Pb}$. The values of these coefficients found in our previous paper were $0.5 \text{ cm}^{-1} \text{ Pb}$ for the secondaries and $2.58 \text{ cm}^{-1} \text{ Pb}$ for their tertiaries. This difference is probably due to the fact that there was a heavy roof over our apparatus composed of an inch of tile, 4 inches of concrete and a ceiling. Hence, most of the secondaries probably came from the materials of the roof instead of the air.

The comparison between the absorption coefficients obtained from the data presented here and those obtained from Rossi's and Funfer's data is interesting. The secondaries produced in the aluminum evidently have a lower energy than the air secondaries in Rossi's and Funfer's experiments. This follows from the fact that μ_a for aluminum, 0.7, is greater than for air, 0.32. The comparison is made with Rossi's and Funfer's results for air instead of our previous results on account of the error due to the heavy roof over our apparatus. We see also that the absorption coefficient of the tertiaries from aluminum secondaries, $2.0 \text{ cm}^{-1} \text{ Pb}$, is greater than that for tertiaries produced by air secondaries, $1.18 \text{ cm}^{-1} \text{ Pb}$.

The particles which produce this effect are charged particles according to Johnson.³ He draws this conclusion from a study of the counting rates with the lead scatterer just below and just above the top counter. If there are any uncharged particles ejecting showers of particles from the lead they would not produce triple coincidences with the lead in the first position since the uncharged particle could not actuate the top counter. If any uncharged particles are present the count with the lead above the top counter should therefore be greater than the count with the lead below it.

Johnson found such an increase. However, he maintains that a correction must be applied to the count with lead above the top counter. With no lead present he assumes all the triple coincidences to be caused by showers created in the material of the top counter. These particles would be absorbed with the lead below the top

counter and unaffected with the lead above the top counter. Therefore, he subtracts the number of coincidences with no lead present from the number with the lead above the top counter. Then he finds the counting rate with lead above the top counter slightly greater than the rate with the lead below the top counter.

It seems probable that some of the coincidences with no lead present are due to showers from the air and any other materials above the counter. Such shower particles would be absorbed equally with the lead in either position.

Johnson's work has been repeated using also a third position of the lead, just above the bottom counter. This position gives another value of the scattering angle and effective area of the lead plate. The three positions of the lead are shown in Fig. 7 and the results in Table III.

TABLE III. Counting rate for different positions of *S*.

POSITION OF <i>S</i>	TOTAL COUNT	TOTAL TIME	RATE
1. JUST ABOVE BOTTOM COUNTERS	330	37.2 hr.	8.87 ± 0.32
2. JUST BELOW TOP COUNTER	479	49.6 hr.	9.66 ± 0.30
3. JUST ABOVE TOP COUNTER	262	18.0 hr.	14.5 ± 0.58

FIG. 7. FIG. 8.

FIG. 7. Arrangement for investigating non-ionizing primaries which cause showers.

FIG. 8. Arrangement for investigating hardness of primaries which produce tertiaries.

There is a substantial increase in the counting rate with the lead just above the top counter as Johnson found. This increase might be ascribed to the fact that the scattering angle is decreased when the lead is moved from beneath to above the top counter. However, the scattering angle was increased even more by moving the lead from position 1 to position 2 and the count was not affected. Hence this was probably not the cause of the increase.

Also there might be an increase due to the edges of the lead plate being effective in position 3 and not in position 2. However, the edges are effective also in position 1 and there is no increase; so this is probably not the cause of the

³ T. H. Johnson, Phys. Rev. 45, 581 (1934).

increasé. Hence, it seems probable that there are non-ionizing particles causing some of the showers. This causes the large increases in counting when the lead is moved from position 2 to position 3.

Recent work by Gilbert⁹ and Johnson⁸ has shown that the production of tertiary particles increases greatly at high altitudes. Johnson compares the intensity of tertiaries (denoted showers by Johnson and Gilbert) at two high altitudes. He finds the ratio of these two intensities the same as the ratio of the intensities of the soft corpuscular component of the primary radiation at the same altitudes. He concludes therefore that the soft corpuscular component is the principal source of showers.

In order to test this conclusion the arrangement of Fig. 8 was employed. Here, the heavy lead block cuts down the intensity of the soft, corpuscular component and does not appreciably affect the intensity of the penetrating cosmic particles. If the primary rays causing the effect were the penetrating component, then they would knock secondaries from the aluminum block as before. These secondaries should have almost the same intensity as when the heavy lead block was not there. This follows since the intensity of the primary penetrating rays is only slightly reduced by 7 cm of lead. Then, these aluminum secondaries should pass through the top counter and eject tertiaries from *S* into the bottom counters.

On the other hand, if the primary particles causing this effect are the soft corpuscular ones, the 7 cm of lead should cut out about $\frac{1}{3}$ of the primary shower-producing rays. These rays should build up aluminum secondaries to an equilibrium value as the thickness of the aluminum is increased. These aluminum secondaries will produce tertiaries in the scatterer *S*.

However, in this experiment it was found that the triple coincidence count increased with the thickness of the aluminum to a maximum and then decreased with greater thicknesses to the chance count.

Table IV gives the results obtained in several different cases.

It is easily seen from these results that the increase is due both to the presence of the

TABLE IV. *Counting rates for different thicknesses of blocks.*

THICKNESS OF TOP Pb BLOCK	THICKNESS OF Al BLOCK	THICKNESS OF Pb SCATTERER	RATE
7	3.8	0.0	16.8±0.6
7	3.8	0.63	18.3±0.6
7	0.0	0.63	16.8±0.6
0	3.8	0.63	27.0±0.8

aluminum and the scatterer. Hence we conclude that the secondary particles from the aluminum are producing showers in the lead scatterer. It will also be noted that the increased count is considerably less than the count without the lead block present.

Next, the variation of this triple coincidence count with the thickness of aluminum was obtained. The results are shown in Table V.

It follows from these results and the results of Table IV that the primary particles causing the showers are probably even softer than the soft corpuscular component of Johnson. We see this from a comparison of Table V with Fig. 3. In Fig. 3 the increase over the chance count for the 0.63 cm Pb scatterer and the 15.5 cm aluminum block is about 7 or a little over 100 percent of the chance count. In Table V, placing the 7 cm of Pb over the 15.5 cm aluminum block completely absorbs the effect so that we merely obtain the chance count. Thus the particles which excited secondaries in the aluminum in the first case being completely absorbed in 7 cm Pb, must be softer than Johnson's corpuscular component which would only be about 33 percent absorbed.

The manner in which the number of coincidences in Table V increases with the thickness of Al and then decreases is difficult to explain. We might explain this decrease of the effect with increased thickness of aluminum in the following way. The aluminum first builds up secondaries to produce showers in the lead and then with increased thicknesses begins to absorb out the primary particles which excite the

TABLE V. *Increase of counting rate due to aluminum block.*

THICKNESS OF TOP Pb BLOCK	THICKNESS OF Al BLOCK	THICKNESS OF Pb SCATTERER	RATE	INCREASE DUE TO Al
7	0.0	0.63	16.8±0.6	—
7	1.27	0.63	19.9±0.7	3.1
7	2.54	0.63	20.9±0.9	4.1
7	3.8	0.63	18.3±0.6	1.5
7	7.6	0.63	16.4±0.6	-0.4
7	15.5	0.63	16.6±0.7	-0.2

⁹ C. W. Gilbert, Proc. Roy. Soc. A144, 559 (1934).

aluminum secondaries. But the primary particles would have to be exceptionally soft to be absorbed by 8 cm of aluminum, and so this explanation contradicts the fact that they were penetrating enough to go through 7 cm of Pb.

Another explanation is that these particles are some kind of radiation excited in the lead block. It has been shown that lead secondaries are not effective in the usual experiments. However, these particles from the lead might be of a non-ionizing nature. Then, they would not be effective in the previous experiment. In this case the non-ionizing particles would have an opportunity to excite ionizing particles in the aluminum. Then, these particles could produce the usual showers in the lead scatterer. This explanation seems rather complex; but it is the only one evident at present.

The non-ionizing character of the rays from the lead block was investigated in the usual way. An aluminum block 2.54 cm thick, was first placed above the top counter and then below it. The same scatterer, a 0.63 cm Pb sheet, was used in both cases. The two counts were: 18.1 ± 0.4 with the aluminum above the top counter and 14.5 ± 0.4 with the aluminum below the top counter which is equal to the chance count. Thus the rays from the lead do not affect the top counter, but they produce rays in the aluminum which do effect it. The rays from the lead must therefore be non-ionizing rays, possibly neutrons.

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The Secondary and Tertiary Particles Produced by Cosmic Rays

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A search, by means of Geiger counters, was made for scattered cosmic rays in the region around a large iron block but no scattering could be detected. Experiments were tried with one counter just above a metal plate and two counters, placed side by side below it. It was found that the metal plate increased the number of triple coincidences between the three counters. The increase in the number of triple coincidences rose to a maximum and then diminished to zero as the thickness of the metal

plate was increased. This effect was observed with plates of lead, tin and aluminum. It was greatest with lead and very small with aluminum. The results can be explained by supposing that secondary particles from the air above the apparatus produce tertiary particles in the metal plate which pass through the lower counters. The absorption coefficient of the air secondaries in lead was found to be 0.5 and that of the lead tertiaries to be 2.58.

THE purpose of this work was to make a study by means of Geiger-Müller counters of the scattering of the cosmic radiation and the production of secondary particles.

Evidence of scattering of cosmic-ray particles was first obtained by Rossi.¹ Johnson and Street² next measured the number of secondaries produced in a scattering experiment making use of a lead scatterer. The work of Schindler³ on the absorption coefficients and the "übergangseffekte" with various materials also shows the production of secondaries. His data have been further examined by Johnson,⁴ who obtains both absorption and production coefficients of the secondary corpuscular radiation.

Later, very definite evidence for the presence of scattered particles accompanying the cosmic

radiation has been established by work with the cloud expansion chamber. This was first done by Skobelzyn⁵ and followed by Mott-Smith and Locher,⁶ Anderson,⁷ and Blackett.⁸ Each of these have found secondary rays issuing from the walls and pistons of their chambers, also from plates placed in the chamber. Recently, Rossi⁹ has worked with the Geiger-counter method on the production of secondaries and has examined them in a number of different ways.

In the first experiments a search was made for scattered particles with two counters one above the other. These define a vertical beam of cosmic rays, and a third counter was placed outside of this beam so that no single particle could pass through all three counters unless it was deviated or scattered after passing through the upper two.

¹ B. Rossi, *Phys. Zeits.* 33, 304 (1932); *Rend. Lincei* 15, 734 (1932).

² T. H. Johnson, and J. C. Street, *Phys. Rev.* 40, 638 (1932).

³ H. Schindler, *Zeits. f. Physik* 72, 625 (1931).

⁴ T. H. Johnson, *Phys. Rev.* 41, 545 (1932).

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

⁶ L. M. Mott-Smith, and G. L. Locher, *Phys. Rev.* 38, 1399 (1931).

⁷ C. D. Anderson, *Phys. Rev.* 41, 405 (1932).

⁸ P. M. S. Blackett, and G. P. S. Occhialini, *Proc. Roy. Soc. A* 139, 699 (1933).

⁹ B. Rossi, *Zeits. f. Physik* 82, 643 (1933).

The three Geiger counters which were used in all the experiments were of the usual copper-sealed-in-glass type with a length of 20 cm and a diameter of 4.8 cm. The coincidences were amplified and selected with a vacuum tube arrangement similar to that which has been described by T. H. Johnson and were then automatically recorded.

The apparatus used is shown in Fig. 1. The scattering material is a large iron block 30.5 cm high, 15 cm wide, and 40 cm long. The top two

FIG. 1. First arrangement of counters. Dimensions in centimeters.

counters were placed so that the beam defined by them passed entirely through the iron block. The third counter was placed just outside this beam as shown in the figure. Alternating runs of 12 hours each were made with the iron block in the path and removed. Any increase in the triple coincidence counting rate must then be due to the iron scattering the rays. However, a slight decrease with the iron present was found. The results are given in Table I.

TABLE I.

	Total count	Interval (hours)	Rate, counts/hr.	Difference, counts/hr.
Absorber in	80	138	0.579 ± 0.044	0.22 ± 0.069
Absorber out	99	124.5	0.799 ± 0.054	

A test was also made with the third counter close to one side of the iron block and 15 cm from its top. With this arrangement the scattering must necessarily occur at a somewhat larger angle. As in the first experiment, the introduction of the iron produced a small decrease in the number of triple coincidences. The results are given in Table II.

TABLE II.

	Total count	Interval (hours)	Rate, counts/hr.	Difference, counts/hr.
Absorber in	155	47.0	3.30 ± 0.177	-0.39 ± 0.268
Absorber out	151	41.1	3.69 ± 0.201	

These results show that there is no appreciable scattering of the cosmic rays after traversing a block of iron 30 cm thick and also that the number of secondary rays emerging from the block was too small to be detected.

Since the probable error is 0.069 per hour (Table I) a change of 0.14 per hour might have been detected. The upper two counters define a beam of cosmic rays of about 30 particles per hour so that 1.4 scattered or secondary particle per 300 incident particles might have been detected.

The decrease of about 0.2 per hour observed is no doubt due to the absorption by the iron of the rays passing through the lower counter which thus reduces the chance count.

According to Heisenberg's theory¹⁰ for electrons having an energy large compared to the binding energy of the electrons in the atom, the number z_1 of secondaries of energy $\geq \epsilon_1$ is given by

$$z_1 = 0.30z(R \cdot s / \epsilon_1) mc^2 \log (\epsilon_0 / \epsilon_1).$$

Here, z is the number of primary particles falling on unit area in unit time, R is the effective range of electrons of energy ϵ_1 , s is the density of the

¹⁰ W. Heisenberg, Ann. d. Physik 13, 430 (1932).

material and mc^2 is the rest energy of an electron. Now, if we consider the first experiment, the path in the iron of a secondary produced at the middle of the block will be approximately 15 cm. The relation connecting this path with the energy has been given by Bohr,

$$R_s = (\epsilon/mc^2)^2 [(z_a + z_k)/sz_a^2]$$

where R_s is the path, ϵ the energy, z_a the atomic number, and z_k the number of electrons in the nucleus. To a rough approximation, we find then for the path of 15 cm, the energy necessary is

$$\epsilon = 1000 mc^2.$$

Since the probable error is 0.07 per hour (Table I), a change of 0.14 per hour might have been detected. The upper two counters define a beam of the cosmic-ray shower in which are 30 particles per hour. Hence, the resolving power of the apparatus may be said to be 0.14/30 or 0.005. On substitution of the above values in Heisenberg's relation, we find

$$z_1/z = 0.3(15 \times 7.8/1000) \log 10,$$

$$\text{assuming } \epsilon_0 = 10,000 mc^2.$$

This fraction must be scattered over an area of approximately 500 square centimeters. Hence, we see that the fraction which would be scattered into the counter of area 96 square centimeters would be approximately 0.016. However, the actual decrease found when the iron was present caused by the change in chance count due to the absorption of particles passing through counters 2 and 3, was of sufficient magnitude to cancel this and give a net decrease.

Experiments were next tried with one counter above a lead plate and two below it as shown in Fig. 2. The two lower counters were placed side by side symmetrically about the vertical plane through the upper counter.

With this arrangement triple coincidences can be produced by a particle passing through two of the counters and producing a secondary particle in the lead which passes through the third counter or by a particle passing through the upper counter and producing two secondaries in the lead plate which pass through the two lower counters one through each.

It was found that the lead plate increased the

FIG. 2. Second arrangement of counters. Dimensions in centimeters.

number of coincidences observed and that the increase depended on the thickness of the plate. The results obtained are given in Table III and are shown graphically in Fig. 3.

TABLE III.

Thickness (cm)	Total count	Interval hours	Rate counts/hr.
0	58	20.0	2.84 ± 0.25
.47	68	9.8	$6.9 \pm .56$
.63	67	8.6	$8.1 \pm .64$
1.1	75	10.0	$7.5 \pm .58$
1.58	68	9.75	$6.85 \pm .56$
2.22	145	25.75	$5.6 \pm .28$
3.2	92	19.75	$4.73 \pm .32$
3.97	55	15.0	$3.7 \pm .31$
5.08	54	14.5	$3.1 \pm .31$
6.8	95	31.32	$3.03 \pm .21$

If the triple coincidences were due to secondaries produced in the lead by the primary cosmic-ray particles, we should expect to get a curve like the dotted line in Fig. 3. The secondaries would gradually build up with increasing thickness of lead until equilibrium with the primaries was reached as shown by the dotted line, which would then fall off slowly with the absorption of the primaries.

The observed curve can be explained, on the assumption that the particles which produce the

FIG. 3. Counts due to tertiaries as a function of thickness of lead plate.

effect are tertiary particles, generated in the lead by light element secondaries produced in the regions above the scatterer. In this case the rise in the curve is due to the building up of the number of tertiaries to the equilibrium value. Then, the decrease with increasing thickness is due to the absorption in the lead of the air secondaries.

The fact that an effect due to the tertiaries produced by the lead secondaries in the larger thicknesses is not detected can be explained by a consideration of their energies. The absorption coefficient of lead secondaries in lead has been calculated by Johnson, and found to be 0.98. This in comparison with the value calculated for air secondaries, namely 0.5, shows the lead secondaries have considerably less energy. It follows from this that the tertiaries formed by the absorption of lead secondaries must have very small energies. Hence, their absorption coefficient in lead must be large, greater than the 2.58 calculated for air tertiaries, i.e., lead tertiaries ejected by air secondaries. Then it follows that only a very thin layer at the bottom of the lead block is effective in ejecting tertiaries due to lead secondaries into the lower counters. The tertiaries formed in this layer are too few to be detected.

The distribution of the particles over horizontal surfaces is uniform; so we need only consider variations over vertical distances. Now, ab-

sorption of the air secondaries in the lead obeys an exponential law with the absorption coefficient, μ_a . This absorption coefficient is also the proportionality factor for the production of tertiaries with respect to the number of secondaries absorbed, since each secondary is absorbed by emitting tertiaries of some form. So we have the total number of lead tertiaries emerging from the bottom of a block of thickness l due to the air secondaries absorbed in a layer of thickness dx at a distance x from the bottom given by

$$dn_t = K\mu_a e^{-\mu_a(l-x)} e^{-\mu_t x} dx,$$

assuming for the tertiaries exponential absorption with coefficient, μ_t . K is here a factor proportional to the number of air secondaries falling on unit area in unit time.

On integration we obtain

$$\begin{aligned} n_t &= e^{-\mu_t l} K \mu_a \int_0^l e^{x(\mu_t - \mu_a)} dx \\ &= e^{-\mu_t l} K \mu_a [1 - e^{-x(\mu_t - \mu_a)} / (\mu_t - \mu_a)], \end{aligned}$$

which on substitution of l for x gives us the total number of tertiaries emerging from the lead

$$\bar{n}_t = K \mu_a e^{-\mu_t l} [1 - e^{-l(\mu_t - \mu_a)} / (\mu_t - \mu_a)].$$

This equation contains two absorption coefficients, μ_a and μ_t , which can be determined from the observed data. By trial and error method it was found that the absorption coefficients required are

$$\mu_a = 0.50, \quad \mu_t = 2.58.$$

Table IV gives the calculated and observed values. From these it is evident that the theory agrees with the experimental values within the experimental errors.

TABLE IV.

Thickness of Pb (cm)	No. tertiaries calculated	Thickness of Pb (cm)	No. tertiaries observed
0.3	3.4	0.47	4.1 ± 0.25
.5	4.15	.63	5.2 ± .56
1.0	5.0	1.1	4.8 ± .58
2.0	3.3	2.2	3.2 ± .28
3.0	2.05	3.0	2.0 ± .32
4.0	1.17	3.97	1.0 ± .31
5.0	0.75	5.08	0.3 ± .31
6.0	.4		
7.0	.22	6.8	.1 ± .21

It is interesting to note that the value of μ , 0.50 agrees exactly with that found by Johnson from an entirely different type of experiment.

A similar series of experiments was made with aluminum instead of lead. A relatively small increase in the triple coincidence rate was found. The results are shown in Table V.

TABLE V.

Thickness of Al (cm)	Total count	Interval hours	Rate counts/hr.
0	257	53	4.85 ± 0.20
.84	111	23	$4.8 \pm .31$
1.68	123	23	$5.35 \pm .32$
3.36	117	23	$5.1 \pm .31$
5.04	152	33.8	$4.5 \pm .25$

Another similar set of experiments was then done with tin as the scatterer. Results are given in Table VI.

The results with lead, tin and aluminum show

TABLE VI.

Thickness of Sn (cm)	Total count	Interval hours	Rate counts/hr.
0	72	20.15	3.6 ± 0.28
.64	134	22.75	$5.8 \pm .34$
1.28	138	20.75	$6.6 \pm .38$
1.92	147	20.6	$7.3 \pm .39$
2.54	97	13.5	$7.0 \pm .73$
3.81	129	20.75	$6.2 \pm .36$
5.08	352	69.0	$5.1 \pm .18$

that the effect varies with the atomic number. This agrees with Heisenberg's theory of absorption, according to which with heavier atoms most of the absorption is due to production of secondary particles. With lighter atoms, the absorption is largely due to "bremsung" or more distant collisions, not ejecting electrons from the material.

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