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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 Street[2] next measured the number of secondaries produced in a scattering experiment making use of a lead scatterer. The work of Schindler[3] on the absorption coefficients and the "uebergangs-effekte" 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 Skobelzyn[5] 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, Rossi[9] 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.

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[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. **A139**, 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 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.

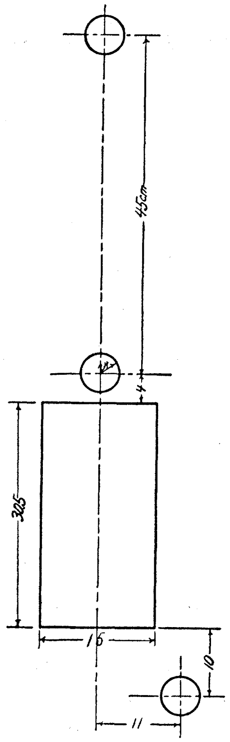

FIG. 1. First arrangement of counters. Dimensions in centimeters.

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 theory[10] 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 $\geqslant \epsilon_1$ 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

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[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.

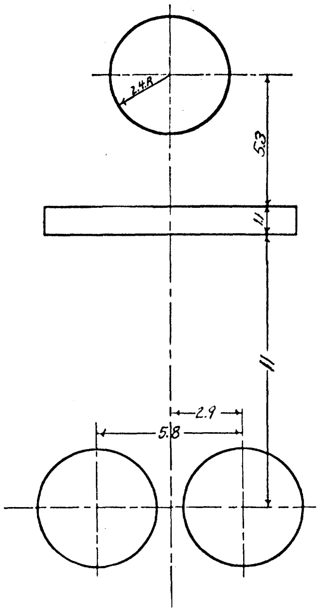

FIG. 2. Second arrangement of counters. Dimensions in centimeters.

It was found that the lead plate increased the 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 ± .56
.63	67	8.6	8.1 ± .64
1.1	75	10.0	7.5 ± .58
1.58	68	9.75	6.85± .56
2.22	145	25.75	5.6 ± .28
3.2	92	19.75	4.73± .32
3.97	55	15.0	3.7 ± .31
5.08	54	14.5	3.1 ± .31
6.8	95	31.32	3.03± .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

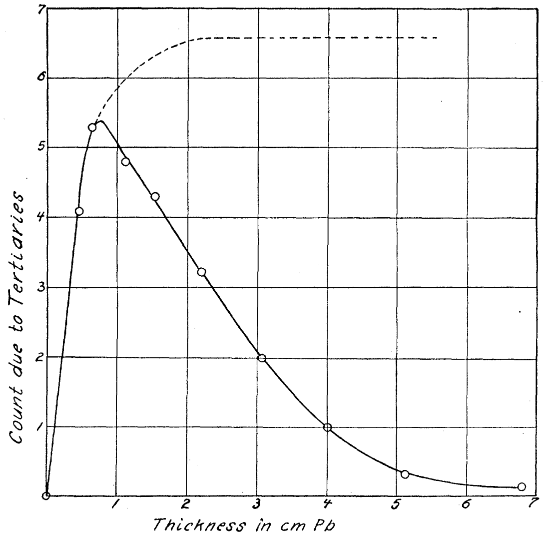

FIG. 3. Counts due to tertiaries as a function of thickness of lead plate.

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, absorption of the air secondaries in the lead obeys an exponential law with the absorption coefficient, μ_s. 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

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

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

$$n_t = e^{-\mu_s l} K\mu_s \int_0^x e^{x(\mu_s-\mu_t)} dx$$

$$= e^{-\mu_s l} K\mu_s [1 - e^{-x(\mu_t-\mu_s)} / (\mu_t - \mu_s)],$$

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

$$\overline{n_t} = K\mu_s e^{-\mu_s l} [1 - e^{-l(\mu_t-\mu_s} / (\mu_t - \mu_s)].$$

This equation contains two absorption coefficients, μ_s 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

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

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_s, 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 ± .31
1.68	123	23	5.35± .32
3.36	117	23	5.1 ± .31
5.04	152	33.8	4.5 ± .25

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

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± .34
1.28	138	20.75	6.6± .38
1.92	147	20.6	7.3± .39
2.54	97	13.5	7.0± .73
3.81	129	20.75	6.2± .36
5.08	352	69.0	5.1± .18

The results with lead, tin and aluminum show 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.

I wish to express my sincere gratitude to Professor H. A. Wilson and to Dr. L. M. Mott-Smith for their interest and valuable suggestions.