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The Absorption of Cosmic-Ray Electrons*

J. C. STREET, R. H. WOODWARD AND E. C. STEVENSON, *Research Laboratory of Physics, Harvard University*

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The interpretation that the coincident discharge of three or more G-M counters in line represents the passage of a single ionizing particle through the counters and any intervening material has been checked by two methods: (1) A vertical cloud chamber between the central and lower counters of a triple-counter telescope controlling the chamber has shown in 90 percent of the coincidences a single electron directed through the counters even when lead up to 45 cm in thickness is placed between the central and upper counters. Soft or hard rays associated with the single particle are rare. (2) Four counters so spaced that 90 cm of material could be introduced between them controlled additional counters which were placed adjacent to the telescope elements and connected as in a hodoscope circuit for the detection of rays associated with those producing the quadruple counts. In only 10 percent of the coincidences were any of the side counters discharged. Absorption data obtained with the latter arrangement for lead, iron and marble ($CaCO_3$) indicate that the absorption as a function of the thickness of absorber on a scale of extranuclear electrons per cm^2 is approximately the same for all three materials. The lead values have been compared with Anderson's electron energy distribution (for the counter controlled data) to determine what specific energy loss values for electrons in lead must be assumed to satisfy both sets of data. The results are:

Average energy loss (MEV) per cm Pb	45	31	25	20
Energy range MEV	0–680	680–1150	1150–1900	1900–2500

INTRODUCTION

IN 1933 Rossi[1] presented in the form of a summary a description of a series of important counter studies of the cosmic radiation at sea level. As a result of these and more recent investigations[2] Rossi has concluded that two-thirds of the penetrating radiation at sea level consists of high energy (sufficient to penetrate at least 10 cm of lead) ionizing corpuscles, and that this corpuscular component is reduced to about half-value in traversing a meter of lead. In 1934 Anderson, Millikan, *et al.*[3] in a report of cloud-chamber observations of cosmic-ray phenomena presented two objections to Rossi's conclusions which may be stated as follows:

(1) Shower processes may account for a large fraction of the coincident counts of a set of Geiger-Müller counters when thick lead absorbers are placed between the units.

(2) It is impossible to reconcile the absorption curve obtained by Rossi with their energy distribution and specific energy loss observations. Recently, however, Anderson has presented a very different energy distribution curve[4] and a higher average specific energy loss for electrons in the range below 300 mev.

Further studies by Rossi,[2] Street and Johnson[5] and others[6] support the original interpretation of single ionizing corpuscles. In view of the need for a definite decision concerning the significance of the counter absorption experiments we have

* Presented at the New York meeting of the American Physical Society, February, 1935. See abstracts Nos. 31 and 32.

[1] B. Rossi, Zeits. f. Physik **82**, 151 (1933).

[2] B. Rossi, Internat. Conf. Phys., London, October, 1934.

[3] Anderson, Millikan, Neddermeyer and Pickering, Phys. Rev. **45**, 352 (1934).

[4] Anderson and Neddermeyer, Internat. Conf. Phys., London, October, 1934.

[5] Street and Johnson, Phys. Rev. **42**, 142 (1932).

[6] D. S. Hsiung, Phys. Rev. **46**, 653 (1934).

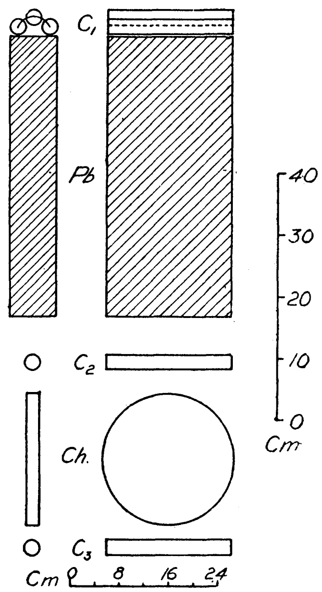


FIG. 1. Geometrical arrangement of counters (C_1, C_2, C_3) absorbing material (Pb), and cloud chamber (Ch).

investigated in detail the phenomena associated with the coincidences of a set of counters when thick absorbers are placed between them. We present in this paper the results of this investigation together with some new observations on the absorption of the fast corpuscles in lead and other materials.

STUDY OF THE COINCIDENCE MECHANISM WITH THE CLOUD CHAMBER

Three counters were placed one above the other in a vertical plane with their axes horizontal. The absorbing material was introduced between the central and upper counters and a vertical cloud chamber was between the central and lower counters. Fig. 1 is a scale drawing of the arrangement. (The upper counter actually consists of three tubes in parallel to increase the solid angle.) In order to reduce secondary effects to a minimum the apparatus was unshielded from above except for a light wooden roof and care was taken to remove dense material from the immediate neighborhood of the counters. The arrangement is therefore well designed to examine the discharge mechanism of the usual coincident counter telescope adapted for absorption measurements. On the basis of Rossi's interpretation the counter-controlled cloud photographs should show single tracks directed in some line through the counters and the absorbing material, whereas if the objections cited above are valid, such single tracks should be absent from most of the photographs.

We have taken photographs with both a 45-cm and a 15-cm lead absorber, 112 in the first case and 107 in the second. With the 45-cm block, 101, or 90 percent, show single rays directed through the counters; with the 15-cm block there are 101, or 94 percent such cases.

These direct observations with thick absorbers show that the first objection of Anderson, Millikan, *et al.* is not valid. Our results are not contradictory to their actual observation that the relative importance of shower produced coincidences is increased by placing one cm of lead between a pair of counters. However, their assumption that showers become increasingly important with thicker absorbers is definitely in error. Auger and Ehrenfest[7] have recently reached the same conclusion from a similar experiment.

It is of some interest to determine the frequency of occurrence of secondary radiation associated with the penetrating corpuscles. This is a difficult problem with a cloud chamber because of the poor time resolving power of the method, but the photographs do give some qualitative information. Many of them show, in addition to the straight track directed through the counters, other tracks of the same apparent sharpness. However, 58 photographs taken at

TABLE I. *Summary of data on photographs.*

	Counter Controlled 45 cm Lead	Counter Controlled 15 cm Lead	Random under 15 cm Lead
Total Photographs	112	107	58
Photographs with a straight track through the lead and counters	101	101	1
Photographs with 1 inclined* ray contemporary with the expansion	24	24	12
Photographs with 2 inclined rays contemporary with the expansion	6	14	6
Photographs with more than 2 inclined rays contemporary with the expansion	3	4	0
Total inclined rays contemporary with the expansions	36	51	24

* By "inclined" rays we mean those directed at such angles that they would not pass through the counters and absorbing material.
β-rays which are obviously soft have not been classified as they are probably due to the normal radioactivity of the air and matter surrounding the chamber.

[7] Auger and Ehrenfest, Comptes rendus **199**, 1609 (1934).

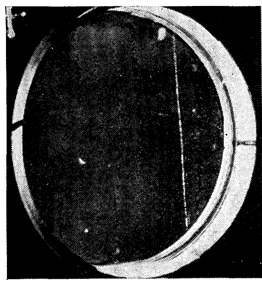


FIG. 2. Single electron track.

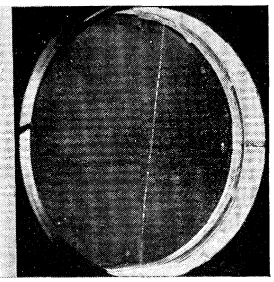


FIG. 3. Single electron track.

random show about the same percentages of soft beta-rays and sharply inclined straight rays apparently contemporary with the expansion. Thus we conclude that, with a thick absorber, complex phenomena actually associated with the single rays through the counters are infrequent.

The complete data are classified and described in Table I. Figs. 2 and 3 are typical examples of straight rays unaccompanied by any other contemporary phenomenon. Fig. 4 shows a straight track and soft electron tracks in addition. Fig. 5 shows a complex shower, the only one observed in 219 photographs.

STUDY OF THE EFFECT OF SHOWERS WITH A HODOSCOPE CIRCUIT

A set of counters, designed for the investigation of the abundance of associated rays, has been constructed as shown in Fig. 6. There are four groups of counters so spaced that six blocks of absorbing material with a total thickness of 91.5 cm can be placed between them. The two central counters in each group are connected in parallel so that they act as a single counter. Quadruple coincidences between the four pairs of central counters are recorded for various thicknesses of absorbing material. The eight outside counters and eight corresponding neon lamps are connected in the same way as the hodoscope unit designed by Johnson and Stevenson[8] and are controlled by the coincidence set. A discharge of an outside counter causes its corresponding neon lamp to flash, provided a quadruple coincidence occurs simultaneously. The lamp flashes are photographed by an automatic camera, each quadruple count advancing the film one frame. The number and positions of the flashes recorded on the film indicate the number and positions of the outside counters which are discharged by rays associated (coincident in time) with the ray or rays which caused the quadruple coincidence. Examination of a total of a thousand frames shows that the flashes are distributed statistically at random among the eight counters—no positions seeming to be preferred. Of 355 frames taken with no absorber between counters 9.5 percent show at least one flash, and 3.6 percent

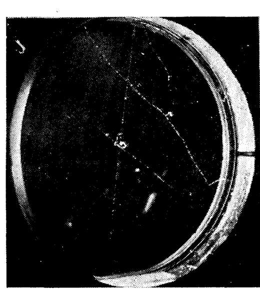


FIG. 4.

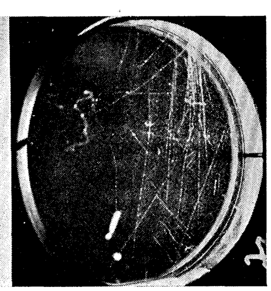


FIG. 5.

FIG. 4. Single electron track with 3 beta-tracks contemporary with the expansion.
FIG. 5. A shower. The heavy tracks are almost certainly old.

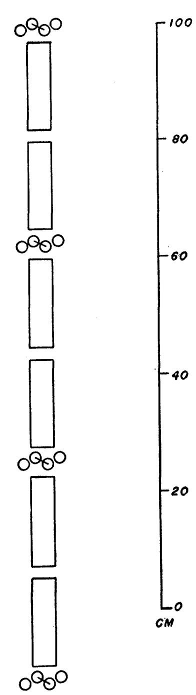


FIG. 6. Arrangement of counters for the measurement of the absorption of cosmic-ray electrons.

[8] Johnson and Stevenson, J. Frank. Inst. **216**, 329 (1933).

show more than one. Of 343 frames taken with 91.5 cm of lead between counters 10.2 percent show at least one flash, and 4.5 percent show several. In an effort to obtain the greatest possible number of associated rays, we placed 1.4 cm of lead (the thickness[1] giving maximum shower production) above the top counters, and observed that 16.8 percent of 326 frames show at least one flash and 9.3 percent show more than one. The probabilities of accidental flashes (0.3 percent and of lamp failures (6 percent entirely due to the inefficiency of the corresponding counters) have been measured in the usual way[9] and corrections have been made. The results indicate that groups of rays coming from the atmosphere and from the absorbing material are comparatively rare, and thus the chance of four counters being discharged simultaneously by associated rays is too small to account for an appreciable part of the observed counting rate. The counting rate is reduced to 3 percent of the original value by displacing the central counters just out of line. Moreover, the relative abundance of associated rays remains approximately constant with various thicknesses of absorbing material, and, therefore, such associated rays cause no appreciable error in the relative counting rates.

Errors due to associated rays at thicknesses near the optimum scattering value may be avoided by building the absorbing material up from the bottom of the unit. Although Fünfer[10] has found some upward scattering, it is small compared to the downward intensity. In fact the introduction of 1.4 cm of lead below the bottom counter was found to produce no observable increase in the quadruple counting rate.

TABLE II. *Absorption of electrons in lead, iron and marble*

	Thickness of absorber (cm)	Electrons per cm² (×10⁻²⁶)	Time (min.)	Quadruple counts	Counts per min.	Probable error	Corrected counting rate
Lead	0.00	0.000	10528	3052	0.289	0.0048	0.289
	1.43	.038	7535	1860	.247	.0056	.245
	15.2	.411	6146	1308	.213	.0038	.209
	30.5	.822	4565	832	.178	.0033	.167
	61.0	1.64	4149	573	.138	.0042	.128
	91.5	2.47	7111	832	.117	.0029	.107
Iron	.00	.00	4071	1140	.280	.0062	.280
	15.2	.337	4534	1058	.234	.0053	.229
	30.5	.674	4391	848	.193	.0041	.181
	61.0	1.35	4053	652	.161	.0044	.149
	91.5	2.02	4448	591	.133	.0066	.122
Marble	.00	.00	4234	1202	.284	.0059	.284
	30.5	.250	7071	1587	.223	.0049	.223
	61.0	.500	4402	911	.207	.0026	.206
	91.5	.750	14536	2938	.202	.0027	.197

[9] Street and Woodward, Phys. Rev. **46**, 1029 (1934).
[10] Von E. Fünfer, Zeits. f. Physik **83**, 92 (1933).

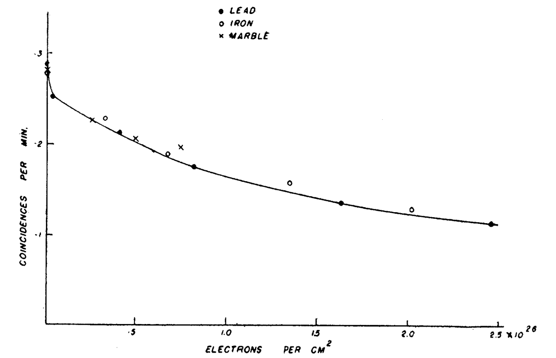


FIG. 7. The absorption of cosmic rays in lead, iron and marble.

As a result of these experiments we conclude in agreement with Rossi[2] that the use of efficient counters in carefully designed quadruple or triple coincidence telescopes will result in data which may be interpreted on the basis of the passage of charged particles through the counters.

NEW ABSORPTION RESULTS OBTAINED WITH THE COINCIDENCE UNIT

In view of this conclusion we have made a more extensive study of the absorption of the fast electrons in three materials. The results for lead iron and marble are tabulated in Table II. The counting rates have been corrected for barometric fluctuation[11] and the probable errors have been estimated from the residuals. The accidental counting rate has been found to be too small 0.00011 per min.) to cause any error, but the change in efficiency[9] of the counters with thickness of absorber (and consequent change of individual rates) has been found to be appreciable. The corrected rates are given in the final column. In Fig. 7 the quadruple counting rates have been plotted against the thickness of absorber expressed in extranuclear electrons per cm². The iron points lie within the probable error of the lead curve, but there is an indication that the absorption per electron of iron is less than that of lead, and that the marble is less absorbing than the iron. If these apparent differences are

[11] Stevenson and Johnson, Phys. Rev. **47**, 578 (1935).

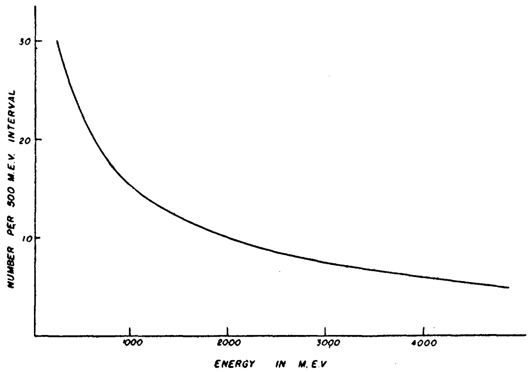


FIG. 8. Anderson's energy distribution of cosmic-ray electrons.

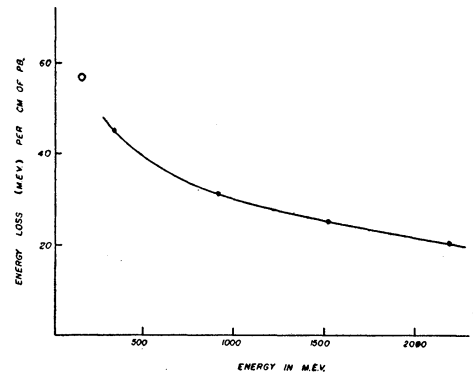


FIG. 9. Specific energy loss for lead as obtained from comparison of the lead absorption curve with Anderson's energy distribution curve.

due to nuclear absorption, the absorption per nucleus increases somewhat more rapidly than linearly with the atomic number.

COMPARISON OF THE LEAD ABSORPTION CURVE WITH THE ENERGY DISTRIBUTION CURVE

Since we are confident that the lead absorption curve is reliable, it is instructive to compare it with Anderson's energy distribution curve.[4] These two curves are related by the energy loss per cm of lead, and, as Anderson has pointed out, are in disagreement, if, as he assumes, the specific energy loss is independent of the energy of the rays. At the International Conference in London, Anderson reported a list of 104 cosmic-ray energy measurements obtained with a counter-controlled cloud chamber. No measurements of energies less than 300 millions of electron volts (MEV) are included, so we have added a reasonable number (30) of low energy rays to the list (this choice of 30 will be justified to a certain extent below) and have plotted the number of rays per 500 MEV interval against the energy of the rays to obtain the smoothed curve given in Fig. 8. Assuming that the penetration of the rays depends on their energies, i.e., that rays of a given energy have approximately the same range and that that range is greater for rays of greater energy, it is possible to determine the specific energy loss as a function of the energy by comparing the lead absorption and energy distribution curves. The first block (15.2 cm) of lead absorbs a definite fraction of the cosmic-ray electrons, and that fraction on the energy distribution curve corresponds to an energy range (0–680 MEV). The second block absorbs a further fraction corresponding to a higher range of energy (680–1150 MEV). Then the average specific energy loss per cm of lead is obtained by dividing the energy loss in the lead block by the thickness. The results are plotted in Fig. 9. The large open circle is an average of Anderson's direct measurements. The choice of 30 low energy electrons to complete Anderson's energy distribution curve below 300 MEV gave the best fit between the initial part of this plot and Anderson's value of 57 MEV per cm. The value 45 MEV on our curve of Fig. 9 is questionable since it depends on the choice of the number of low energy electrons, but the other values are only slightly influenced by that number. All of Anderson's nine measurements of the specific energy loss reported at London were obtained from observations of rays of energy less than 300 MEV. They fluctuate from 18 (less than our lowest value) to 120 MEV per cm. Thus we may consider our results as an extension of the average specific energy loss to higher energies. Consideration of the curve and Anderson's fluctuating values leads to the speculation that fast electrons may lose energy by two processes: (1) Encounters with extranuclear electrons resulting in a nonfluctuating energy loss, probably independent of the energy, and which has a value of about 18 MEV per cm; and (2) nuclear or possibly close electron encounters with large energy losses (due to radiation or pair production), the probability of these encounters decreasing with increasing energy.

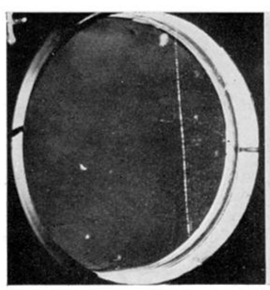


FIG. 2. Single electron track.

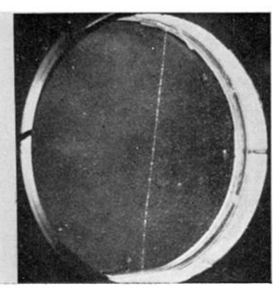
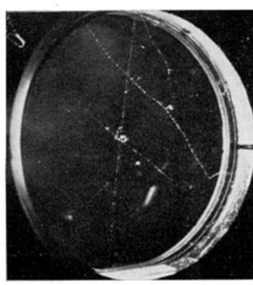
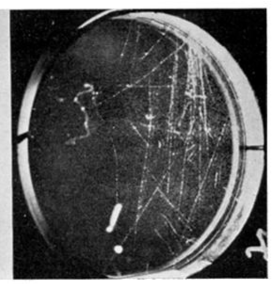


FIG. 3. Single electron track.





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